INVESTIGATION OF HOLOCENE FAULTING

PROPOSED C-746-U LANDFILL EXPANSION

Paducah Gaseous Diffusion Plant

Paducah, Kentucky

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EXECUTIVE SUMMARY

This report presents the findings of a fault hazard investigation for the C-746-U landfill's proposed expansion located at the Department of Energy's (DOE) Paducah Gaseous Diffusion Plant (PGDP), in Paducah, Kentucky. The planned expansion is located directly north of the present-day C-746-U landfill. Previous geophysical studies within the PGDP site vicinity interpret possible northeast-striking faults beneath the proposed landfill expansion, although prior to this investigation the existence, locations, and ages of these inferred faults have not been confirmed through independent subsurface exploration. The Code of Federal Regulations (CFR), Subtitle D, Title 40, Part 258, subpart B (258.13) requires that disposal facilities (such as the C-746-U landfill and possible expansions) be located more than 200 feet from a fault that has had surface displacement within Holocene time (i.e., approximately the past 11,000 years). The purpose of this investigation is to assess whether or not Holocene-active fault displacement is present beneath the footprint of the proposed landfill expansion. This information can be used to address compliance of the proposed expansion with CFR, Subtitle D, Title 40, Part 258, subpart B (258.13). The investigation was completed as a collaborative effort involving William Lettis & Associates, Inc., the Geology Department of the University of Kentucky, the University of Kentucky-Kentucky Research Consortium Energy and Environment (KRCEE), and the University of Chicago. Technical peer review of the approach, methods, results and conclusions of this study have been provided by scientists and technical experts with the Kentucky Geological Survey, the Illinois Geological Survey, the University of Memphis, the University of Illinois – Champaign, Science Applications International Corporation (SAIC), and M. Tuttle & Associates.

The geologic assessment included (a) review of relevant geologic and geotechnical data from the site vicinity, (b) analysis of detailed aerial photography, (c) field reconnaissance of the site vicinity and other important sites of previous investigations, (d) collection and stratigraphic analysis of 86 subsurface sediment cores, (e) laboratory chronological (age-dating) analyses, and (f) preparation of this report. All of these activities were completed at or above the accepted standard-of-practice for geologic investigations in the mid-continent region; overall this investigation represents an effort that exceeds previous levels of investigation for site-specific fault-rupture assessments in the mid-continent. Detailed subsurface geologic information was collected along several transects at the proposed landfill site to define buried strata and assess the possibility of fault-related differences in elevation of the strata. Stratigraphic data were collected from 86, 30-ft-long continuous soil cores (a total of 2,580 feet) using direct push technology (DPT). The DPT coring method involves pushing a hollow, 1-11/16 inch

diameter, cylindrical coring tube into subsurface material and extracting the core sample for laboratory analysis. Immediately upon extraction at the proposed landfill site, the cores were sealed and transported to the Kentucky Geological Survey Core Laboratory (in Lexington), where they were unsealed and analyzed for lithologic and pedogenic (soil) characteristics. The analytical process included simultaneous exposure of multiple cores, arranged within the laboratory facility according to depth and position along a given transect, and detailed logging of each core in its entirety. This arrangement facilitated core logging and enabled definitive correlation of stratigraphy among several cores. Strata exposed by the cores are identified and differentiated based on lithologic characteristics, such as grain size (texture), sorting, color, contact irregularities, soil (pedogenic) structure, pedogenic clay or iron-oxide accumulation, and other characteristics. A total of 12 samples of wind-blown loess deposits were sent to the University of Chicago for age-dating via the optically stimulated luminescence (OSL) dating method.

Geologic cross-sections prepared from the DPT data identified laterally continuous horizontal strata for assessing the possibility of fault displacement, and for evaluating the timing of such displacements. Seven primary geologic units are present beneath the site at depths of less than 30 ft, as generalized in the table below. Based on the OSL age-dating analyses, the deposits encountered in the cores range in age from about 16 ka to greater than 125 ka (see table below), which is in good agreement with ages determined for similar loess and fluvial packages elsewhere in the central United States.

Unit Name	Unit Number	Depth Below Ground Surface (Feet)	Unit Age (1000 x years)	Potential Fault- or Fold-related Deformation?	Number of Potential Fault-related or Fold-related Features
Upper Peoria	Unit 1	0– 6	15.4 – 25.2	No	0
Lower Peoria	Unit 2	7 – 9	21.8 – 30.9	Possibly	1
Roxana Silt	Unit 3	9 – 11	32.1 – 50.7	Possibly	3
Unnamed Intermediate Silt	Unit 4	12 –13	53.6 – 75.5	Possibly	14
Metropolis Formation	Units 5.1, 5.2, and 5.3	≥15	≥125 – 180	Possibly	25

Geologic cross-sections developed from the DPT data show that the upper three units (i.e. the Upper Peoria Loess, Lower Peoria Loess, and Roxana Silt) generally are flat-lying and mantle pre-existing topography. In contrast, the lower, older units (Unnamed Intermediate Loess and the Metropolis

Formation) exhibit occasional subtle to abrupt undulations of basal contacts, which may reflect fluvial processes and/or tectonic-related deformation. The geologic cross sections allow for as many as four folds and 21 features with noticeable elevation changes along stratigraphic and/or pedologic boundaries, as summarized in the table above. These possible elevation changes represent differences in the elevation of a given stratigraphic boundary that exceed the uncertainty in the boundary depths based on laboratory measurements, and thus probably are related to natural (tectonic or non-tectonic) processes.

Of the 25 features interpreted to represent elevation changes of stratigraphic boundaries within the Metropolis Formation (units 5.1 to 5.3), 14 may extend upward into the Unnamed Intermediate Silt (unit 4). Similarly, only three of these 14 features possibly extend upward into the Roxana Silt (unit 3) and only one may extend into the Lower Peoria Loess (unit 2). None of the features extends into the Upper Peoria Loess. Any of these 25 features may have formed as a result of non-tectonic processes, such as local fluvial or wind erosion. In particular, the three elevation changes in the base of the Roxana Silt are unlikely to be related to fault displacement, because the sense of vertical separation differs among the various boundaries. Also, if any of these features were to be interpreted as a fault, it would have an anomalously shallow dip, and thus the differences in sense of displacement upsection would imply both normal and reverse faulting, depending on the stratigraphic level. The absence of similar elevation differences elsewhere in the sections lends support to the interpretation of a non-tectonic origin for these three features.

Therefore, if late Quaternary displacement has occurred beneath the site, the most-recent displacement occurred following deposition of the Unnamed Intermediate Silt between approximately 53,600 and 75,500 years ago. Although unlikely, the data do not preclude the possibility of displacement of the Roxana Silt beneath the site, which is approximately 34,600 to 47,200 years old. There is no perceptible displacement of the base of the Upper Peoria Loess, which is approximately 16,600 to 23,500 years old. If late Pleistocene faulting occurred at the site, the age of such deformation would be similar to the youngest age of faulting previously interpreted along northeast-striking faults in southern Illinois.

Thus, the detailed coring data collected during this investigation show no evidence for Holocene (<11,000 years) displacement along previously interpreted faults underlying the site. The data and interpretations do not preclude the possibility of late Pleistocene displacements at a few localities beneath the site, although the stratigraphic elevation changes may also be interpreted as stratigraphic variability related to erosional or depositional processes. Based on these data, we conclude that the latest Pleistocene strata have not been displaced, and that faults beneath the site, if they exist, have been inactive during the Holocene. On the basis of the findings of this study, and in compliance with Code of Federal Regulations (CFR), Subtitle D, Title 40, Part 258, subpart B (258.13), a setback of 200 feet from the previously interpreted faults is not warranted.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

1.0 INTRODUCTION

This report presents the results of a fault rupture hazard investigation for Holocene faulting across a proposed expansion at the C-746-U landfill, in Paducah, McCracken County, Kentucky. The existing C-746-U landfill is a Class II solid waste facility that is operated by the Paducah Gaseous Diffusion Plant (PGDP), and owned by the U.S. Department of Energy (DOE). The site is located approximately 4 miles south of the Ohio River and approximately 10 miles west of Paducah in western Kentucky (Figure 1). The DOE-owned property encompasses 3,600 acres of which 750 acres are occupied by an uranium enrichment facility (PGDP) that lies within a restricted area (Figure 2). The proposed landfill expansion lies outside of this restricted PGDP area and is directly adjacent to a wildlife management area managed by the Commonwealth of Kentucky. The proposed landfill expansion area of interest for this fault study lies directly outside of the operating C-746-U landfill along its western and northern perimeters, and north of two inactive PGDP landfills (Figure 2).

1.1 Purpose

The purpose of this investigation is to assess the presence or absence of Holocene active faulting across the footprint of the proposed C-746-U landfill expansion. Seismic reflection profiles previously acquired and interpreted by Blackhawk Geosciences (2003) suggest two faults (Fault 1 and Fault 2) offsetting Quaternary to Tertiary (Mounds Gravel) deposits beneath the project area (defined as the west-central part of the C-746-U landfill) (Figure 2). However, the existence, locations and ages of these inferred faults have not been confirmed through independent subsurface exploration; thus, the intent of this latest fault hazard investigation is to comply with Code of Federal Regulations (CFR), Subtitle D, Title 40, Part 258, subpart B (258.13) which states:

New MSWLF (Municipal Solid Waste Landfill Facility) units and lateral expansions shall not be located within 200 feet (60 meters) of a fault that has had displacement in Holocene time unless the owner or operator demonstrates to the Director of an approved State that an alternative setback distance of less than 200 feet (60 meters) will prevent damage to the structural integrity of the MSWLF unit and will be protective of human health and the environment. (Note that Holocene time means the most recent epoch of the Quaternary period, extending from the end of the Pleistocene Epoch to the present. This generally refers to the last 11,000 years.)

1.2 Scope of Work

The primary purpose of this investigation is to evaluate the absence or presence of Holocene faulting at the site of the proposed C-746-U landfill expansion. The suitability of the C-746-U landfill with respect to fault location and age was evaluated following regulatory criteria provided in the 2005 Code of Federal Regulations, Subtitle D, Title 40, Part 258, subpart B (258.13). These regulations emphasize the importance of identifying any Holocene active fault that could produce primary surface fault rupture within 200 feet (61 m) of the proposed landfill footprint. If large displacements were to occur beneath the site, such ruptures presumably would damage the integrity of the liner as well as monitoring and waste collection systems, possibly leading to groundwater movement between the landfill and surrounding geologic strata. The purpose of the fault investigation is to assess the location and Holocene activity of previously interpreted Faults 1 and 2 at the site, and provide recommendations, if necessary, for setback conditions in compliance with CFR, Subtitle D, Title 40 for surface-fault rupture hazard (e.g., ground rupture along a surface fault trace).

Our scope of work was designed to focus on previously interpreted near-surface faults intersecting the proposed landfill expansion and was outlined in our proposal dated September 30, 2004 to the Geology Department of the University of Kentucky, and University of Kentucky-Kentucky Research Consortium Energy and Environment (KRCEE). The scope of work for the project consisted of the following:

- Compile and review existing subsurface data obtained from previous geologic and geotechnical investigations of the site and surrounding vicinity. Analysis of readily available aerial photography (November 2001 vintage) provided by KRCEE to evaluate the Quaternary geology and geomorphology in the direct vicinity of the PGDP site and to provide guidance on the appropriate investigation plan.

- Conduct field reconnaissance of the site area to provide relevant information on the type, location, and bedding of existing bedrock and surficial deposits in the direct vicinity of the site, and to assess possible logistical constraints imposed on the project.

- Conduct field reconnaissance of the Barnes Creek fault zone on April 20, 2005 in Massac County, southern Illinois with Mr. John Nelson of the Illinois Geological Survey to obtain a general understanding of the findings of several recent geologic studies performed along this fault zone.

- Augment available subsurface site data by collecting and logging 86 closely spaced direct push technology (DPT) cores along the northern and western perimeters of the existing C-746-U landfill, in September and October 2005. In lieu of permitting the excavation and documentation of an exploratory trench at a DOE facility, the drilling program was designed to evaluate the presence or absence of vertical separation across the previously inferred faults. Four of the 86 cores were drilled for the purpose of collecting sediment (loess deposits) for dating by the optically stimulated luminescence (OSL) technique.

- Prepare this report summarizing the results of the fault-rupture hazard study.

1.2.1 Geologic References Reviewed

We reviewed published maps and literature pertaining to geologic and seismic conditions in the project area. As part of our study, we reviewed the following:

- "Seismotectonic Investigation Report for Siting of a Potential On-site CERCLA Waste Disposal Facility at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky", prepared by SAIC, dated March 2004.

- "Technical Memorandum for the C-746-U Landfill Fault Study at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky", prepared by Bechtel Jacobs Company, LLC, October 2003.

- "Final Shear Wave Seismic Survey Report C-746-U Landfill Seismic Assessment, Paducah Gaseous Diffusion Plant, Paducah, Kentucky", prepared by Blackhawk Geoservices, dated October 2003.

- "Archival Photo Analysis Paducah Gaseous Diffusion Plan", prepared by U.S. Army Corps of Engineers, September, 2000.

- "Acquisition of SH-wave Seismic Reflection and Refraction Data in the Area of the Northeastward Trending Contaminant Plume at the PGDP", prepared by Langston and Street, dated July 31, 1998.

- "Geologic Features Relevant to Ground-water Flow in the Vicinity of the Paducah Gaseous Diffusion Plant", prepared by Drahovzal and Hendricks, 1996.

- "Paducah Gaseous Diffusion Plant, Notice of Intent Application, 1995, Solid Waste Landfill"

- "Application for a Solid Waste Landfill, Notice of Intent to Apply (application form dated 1992): Hazardous Solid Waste Landfill Subsurface Investigation Report", prepared by SAIC, February 1994

We also consulted a variety of other unpublished reports and references pertaining to the geology and hydrogeology of the vicinity of the PGDP site. A list of selected references is presented in "Section 9, References." Some of the data contained in the referenced reports were used and relied upon during our geologic evaluation of conditions affecting the proposed landfill expansion. The locations of nearby geotechnical borings and monitoring wells are shown on Plate 1.

1.3 Acknowledgments

This fault hazard investigation, performed by WLA, was managed by Dr. Ed Woolery of the University of Kentucky, Department of Geological Sciences, and Mr. Steve Hampson of the University of Kentucky-Kentucky Research Consortium for Energy and Environment. John Baldwin, Keith Kelson, Robert Givler, and Sean Sundermann of WLA performed the data collection, analysis and reporting for the fault hazard study. The execution of the field work was accomplished by KRCEE's other subcontractors which included: Science Application International Corporation, Inc. (SAIC) oversaw the Field Operations Management; Miller Drilling Company drilled the DPT cores; and Tricord, Inc. oversaw Health and Safety. Data collection and interpretation of the cores by WLA also included a technical peer review by a three-person internal review panel consisting of Mr. John Nelson of the Illinois State Geological Survey (ISGS), Dr. Roy Van Arsdale of the University of Memphis, and Dr. Martitia Tuttle of M. Tuttle & Associates. This included a review of logged cores at the Kentucky Geological Survey core library and this report. Additional peer review services were provided by Dr. Leon Follmer of the ISGS, Dr. Steve Forman of the University of Illinois, at Chicago, Dr. David Amick of SAIC, and Mr. Marshall Davenport of Jacobs Engineering.

2.0 REGIONAL SETTING

2.1 Regional Seismotectonic Setting

An understanding of the regional seismotectonic setting is essential for evaluating the style, pattern and timing of deformation that previously has been interpreted (i.e., Faults 1 and 2) in the vicinity of the proposed landfill expansion. Faults 1 and 2 lie at the northern margin of the Mississippi embayment, near the transition zone between two late Precambrian-early Paleozoic rifts (i.e., the Reelfoot rift and Rough Creek graben) and the southernmost part of the Illinois Basin (Stearns, 1957; Stearns and Marcher, 1962; Braile et al., 1982; Kolata and Nelson, 1991; Potter et al., 1997; Kolata and Hildenbrand, 1997) (Figure 3). The northeast-trending Reelfoot rift includes the active New Madrid seismic zone (NMSZ) located about 100 km southwest of Paducah (Ervin and McGinnis, 1975; Kane et al., 1981; Hildenbrand et al., 1982); however, bands of contemporary microseismicity associated with the NMSZ project northeast toward Paducah (Wheeler, 1997) (Figure 3). The Illinois Basin includes the Wabash Valley fault zone (McBride et al., 1997). Faults within the Wabash Valley fault zone have been shown to terminate at the intersection of the northern margin of the Rough Creek graben, 60 km north of the PGDP, and thus are not considered a surface-fault rupture hazard at the C-746-U landfill (Hildenbrand and Ravat, 1997). The Rough Creek graben lies directly northeast of Paducah and is relatively aseismic (Wheeler, 1997) (Figure 3).

Within the intersection between the Reelfoot rift and Rough Creek graben, and directly to the north-northwest of Paducah in southern Illinois, is an approximately 40-km-wide zone of steeply dipping, northeast-striking bedrock faults that comprise the Fluorspar Area fault complex (FAFC) (Kolata and Nelson, 1991) (Figure 3). The FAFC was active during the latest Proterozoic to early Cambrian (several hundred million years ago), coincident with the formation of the northeast-striking faults associated with the Reelfoot rift. These faults were reactivated during late Pennsylvanian (290 to 300 million years ago) and Permian (250 to 290 million years ago) time in response to the Alleghenian orogeny. This episode of deformation produced displacements of Paleozoic bedrock in excess of 800 meters, through a combination of normal, reverse and strike-slip faulting, and also included ultramafic igneous activity. In Cretaceous time (65 to 135 million years ago), the Reelfoot rift was reactivated and underwent subsidence, forming the Mississippi embayment. More recently, some faults within the Reelfoot rift (i.e., the NMSZ) have been reactivated in the Quaternary and, consequently, northeast-trending faults, including some within the FAFC exhibit evidence of Quaternary displacement (Nelson et al., 1999). A key question and the focus of this study is to determine if the faults identified below the landfill offset Holocene stratigraphy.

Several faults within the FAFC, such as the Lusk Creek, Raum, Hobbs Creek and Barnes Creek fault zones are postulated to extend southwest across the Ohio River into western Kentucky close to the PGDP facility (Nelson et al., 1999; McBride et al., 2002) (Figure 4). These fault zones consist primarily of high-angle, northeast-striking normal faults that bound northeast-striking horsts and grabens, with a fewer number of reverse and strike-slip faults (Nelson, 1991; Potter et al., 1997; Nelson et al., 1997 and 1999; McBride et al., 2002). Nelson et al. (1999) interpret the graben as pull-apart structures produced by strike-slip faulting, however no master fault is proposed or has been identified to date (Potter et al., 1997; McBride et al., 2002). Thus, during the interpretation of DPT core data collected during this study, both oblique dextral strike-slip and dip-slip displacements accompanied by warping and folding were considered. Models that include pure dextral strike-slip faulting, however, were not considered as a possible mode of deformation because of the preponderance of regional and local seismic reflection data that strongly suggests oblique-slip displacement as the primary style of deformation.

Recent seismic reflection studies in the PGDP site vicinity and south of the Ohio River by Langston and Street (1998) and Woolery and Street (2002) provide evidence for the southwest projection of FAFC structures into western Kentucky (Figures 2 and 4). On the seismic reflection profiles, near-vertical, northeast-striking faults are interpreted to displace Quaternary reflectors, extending within approximately 25 feet (7.6 m) of the ground surface (Woolery and Street, 2002). These northeast-trending faults and structures exhibit a similar structural style to faults identified in the FAFC of southern Illinois. Drahovzal and Hendricks (1996) further suggest that some of these northeast-trending structures in western Kentucky displace Tertiary alluvium and may act as migratory pathways for contaminant plumes at the PGDP facility.

On the basis of similar fault orientations and tectonic origin with the failed Reelfoot rift, some workers have postulated that faults within the FAFC may connect with active northeast striking faults that presently accommodate strain within the NMSZ (Potter et al., 1995; Wheeler, 1997). If true, faults associated with the FAFC may be Holocene active, and preferentially oriented for accommodating dextral strain within the central United States. For instance, Wheeler (1997) interprets faults within the FAFC align with the projection of a northeast-trending band of microseismicity that extends from the NMSZ in southeastern Missouri into western Kentucky (Figure 3). The possible association of northeast-trending

NMSZ contemporary microseismicity aligned with northeast-striking faults in western Kentucky, suggests that some of the FAFC faults may accommodate Holocene deformation (Wheeler, 1997); however, recent studies by Nelson et al. (1999) and McBride et al. (2002) do not support this interpretation and find no evidence of faulting along several FAFC structures within the past 55,000 to 128,000 years. In river valleys east of Paducah, sand dikes exist that cut sediment mapped as Pleistocene and recent fluvial and lacustsrine depostis (Amos and Wolfe, 1966; Amos and Finch, 1968; Olive, 1966). The sand dikes are somewhat weathered and do not appear to be historical in age. Radiocarbon dating of the sediment adjacent to dike terminations indicated that most, if not all, of the liquefaction features formed within the past approximately 4,850 years (M. Tuttle, written communication, 2006). The timing, source, and magnitude of the late Holocene earthquake that induced this liquefaction east of Paducah have not yet been determined M. Tuttle, written communication, 2006). To summarize, regional and local geologic and geophysical studies support a seismotectonic model in which northeast-striking faults of the FAFC, which were active during the Quaternary, extend southwest into western Kentucky close to the C-746-U landfill (Figure 4).

2.2 Fluorspar Area Fault Complex

Several fault evaluation studies performed in the FAFC provide valuable information on the style, geometry and timing of faulting that is directly applicable to assessing the faults interpreted to underlie the C-746-U landfill. For instance, recently identified faults in western Kentucky are interpreted to have orientations and patterns of deformation similar to the northeast-striking fault zones identified in southern Illinois. At least four fault zones (e.g., Barnes Creek, Hobbs Creek, Raum and Lusk Creek fault zones) of the FAFC have been extensively studied by the Illinois Geological Survey, the United States Geological Survey and SAIC (2004) (Figure 4). Nelson et al. (1999) defines the FAFC as consisting of relatively long, narrow grabens bounded by both normal and reverse faults that formed as “pull-apart” structures in response to poorly understood oblique strike-slip faulting. To date, no master strike-slip fault, or direct evidence of strike-slip faulting has been documented to validate this interpretation. It is based primarily on circumstantial evidence that includes an assumed regional stress orientation that would be similar to present-day orientation, and a structural pattern of deformation best explained by transtension deformation (i.e., pull-apart basins along step-overs). Brief descriptions of the four primary fault zones of the FAFC are provided below, including the Barnes and Hobbs Creek fault zones, which project southwest near or through the proposed landfill expansion (Figure 4).

2.2.1 Barnes Creek Fault Zone

The 25-mile-long (40 km), northeast-trending Barnes Creek fault zone is located about 6 miles (10 km) northeast of the proposed landfill expansion (Figure 4). The fault zone is defined as a complex system of grabens and horsts that merges to the southwest with the Hobbs Creek fault zone north of Metropolis, Illinois. The Barnes Creek fault zone is characterized as a zone of narrow (100-to 200-ft-wide) to relatively broad (650-to 980-ft-wide) N20E°- to N40°E-trending grabens bound by high-angle normal and reverse faults (Sexton et al., 1996; Nelson et al., 1999; McBride et al., 2002). Based on borehole data, vertical separation is inferred to be as much as 95 feet (29 meters) for the Metropolis Formation and less than 5 feet (1.5 meters) for the Sangamon Geosol (Nelson et al., 2002). The Barnes Creek fault zone has been the focus of numerous detailed geologic and paleoseismic investigations to assess activity (Nelson et al., 1997 and 1999; SAIC, 2004). Based on creek bank exposures, geophysical profiles and geologic cross-sections supplemented with geotechnical borehole information, McBride et al. (2002) interpret the fault zone as displacing Cretaceous through lower Pleistocene stratigraphy.

As part of a study for a proposed PGDP Site 3A landfill, SAIC (2004) performed a subsequent study of the Barnes Creek fault zone that included additional acquisition of geophysical, ground penetrating radar and borehole data, as well as interpretation of the same creek bank exposures of Nelson et al. (1997 and 1999). The Barnes Creek study by SAIC (2004) concludes that some faults offset Holocene-age deposits. Our reconnaissance-level review of the same exposures with J. Nelson in March 2005 suggests that while relatively young geologic deformation is present, SAIC's (2004) interpretation of Holocene faulting is equivocal. We base this interpretation on: (1) an apparent absence of faulting observed in the upper younger deposits (i.e. presence of only a fracture); (2) uncertain origin of observed fractures (e.g., possibly related to roots); and (3) absence of distinct stratigraphic offset of Holocene deposits.

2.2.2 Hobbs Creek Fault Zone

The southern portion of the 43-mile-long (70 km) Hobbs Creek fault zone is defined by the Massac Creek graben (Nelson et al., 2002) (Figure 4). The Massac Creek graben consists of an approximately N30°E-trending, 2,300 ft-wide (700 m) graben occupied by a complex zone of high-angle normal and some reverse faults that displace Mississippian limestone, Cretaceous McNairy Formation and Pleistocene Metropolis Formation. Based on borehole and geophysical data, the Metropolis Formation is interpreted to be vertically displaced as much as 100 feet (30 m) (Nelson et al., 2002). A review of the geologic map of Nelson et al. (2002) shows that the Tertiary-Quaternary Mounds Gravel exhibits an apparent rightlateral deflection of up to 0.62 mi (1 km) across the Massac Creek fault zone. The Massac Creek graben is mapped as far southwest as the city of Metropolis based on the interpretation of city water wells, alignment of the valley walls of Massac Creek, and local exposures showing offset Metropolis Formation (McBride et al., 2002). The trend of the Massac Creek graben projects about 1.6 mi (2.5 km) east of the proposed C-746-U landfill (Nelson et al., 2002) and may correlate with a similar-sized graben imaged by Langston and Street (1998) (Figure 4). Geologic cross-sections developed from geotechnical borings aligned across the Massac Creek graben show no elevation changes in the overlying Wisconsin loess or Holocene alluvium. Therefore, McBride et al. (2002) and Nelson et al. (2002) interpret this structure to be inactive during the Holocene. The Massac Creek graben appears to have been inactive for at least 75,000 years (Nelson et al., 2002).

2.2.3 Raum Fault Zone

The 50-km-long Raum fault zone is about 4.3 mi (7 km) west of the Hobbs Creek fault zone in southern Illinois (McBride et al., 2002) (Figure 4). On the basis of seismic reflection and borehole profiles, the fault zone is characterized as a 1.0 mi-wide (1.6 km) zone of north- to northeast-trending, steeply dipping faults bounding horst and graben structures. Faults displace Paleozoic bedrock and apparently continue upsection into the overlying Quaternary Metropolis Formation (McBride et al., 2002). Stratigraphic contacts associated with late Pleistocene loess and late Pleistocene to Holocene alluvium show no evidence of displacement across the Raum fault, indicating this fault zone is not active during the Holocene.

2.2.4 Lusk Creek Fault Zone

The northwestern boundary of the FAFC is bound by the Lusk Creek fault zone (Figure 4). Geophysical profiles and boreholes show the fault zone is characterized by subparallel high-angle normal and reverse faults with vertical displacements of up to 230 ft (70 m) in the Cretaceous McNairy Formation, and possibly up to about 16 ft (5 m) of the Pleistocene Metropolis Formation (McBride et al., 2002). The fault zone is composed of numerous, 330 to 980 ft-wide (100-to 300-m) grabens that displace the middle Pleistocene Metropolis Formation, but do not appear to offset overlying late Pleistocene loess deposits.

2.3 Fault Studies at the PGDP in Western Kentucky

Several local and site-specific fault studies have been performed in the vicinity of the PGDP facility (Figure 2). These investigations consisted mostly of geophysical surveys to identify subsurface structures aligned with faults mapped or imaged in southern Illinois. In addition, a site-specific fault hazard study was performed by SAIC (2004) at the existing PGDP facility located south of the proposed C-746-U landfill. In general, these studies suggest possible evidence for a southwest continuation of the FAFC into western Kentucky. For instance, Langston and Street (1998) and Woolery and Street (2002) image numerous northeast-striking, steeply dipping faults bounding horst and graben structures at and near the PGDP facility (Figure 2). Faulting near the PGDP facility typically is interpreted as extensional, with a smaller number of contractional structures. Many of the normal faults can be traced upsection into the Quaternary Metropolis Formation and possibly into overlying Pleistocene loess deposits (Woolery and Street, 2002). Langston and Street (1998) postulate that some of the fault zones act as preferential pathways for contaminants in the Mounds Gravel and Metropolis Formation, providing further evidence that the faults may displace Neogene fluvial deposits.

Site-specific fault studies at the PGDP facility using geophysical data and cross-sections prepared from DPT cores (SAIC, 2004) for the proposed Site 3A landfill in the southern part of the facility interpret as many as 6 to 11 potential north to northeast-striking faults (Figure 2). SAIC (2004) interpret narrow structures bounded primarily by normal faults exhibiting down to the east vertical displacement. Several of the faults are interpreted as extending upsection into the Metropolis Formation, and based on S-wave profiles interpreted by SAIC (2004). On the basis of limited DPT core data, SAIC (2004) concludes that the "study did not find Holocene-age displacement of faults at Site 3A" and that faulting is interpreted to extend within 20 feet (6.1 m) of the ground surface. However, SAIC (2004) also interpret possible post-Metropolis faulting exposed in stream cuts bordering Barnes Creek, approximately 10 km northeast of the PGDP (Figures 1 and 4). Collectively, these previous studies suggest the presence of northeast-striking normal and reverse faults of Quaternary age near the C-746-U landfill that may be laterally continuous with the FAFC in southern Illinois (Figure 4).

2.4 Geomorphology of the FAFC

The regional landforms of this part of the central United States are dominated by numerous large fluvial systems (Ohio, Cache, Obion and Tennessee Rivers) that have coursed toward the Mississippi embayment throughout much of the late Pleistocene (Saucier, 1996; Frye et al., 1962; Fisk, 1944; Esling et al., 1989; Autin et al., 1991; Blum et al., 2000). The ancestral course of the Ohio River represents a prominent physiographic feature that trends oblique across the FAFC in southern Illinois. The ancestral Ohio River once flowed westward through the Cache Valley northwest of its present-day location, and transported outwash deposits from Wisconsin glaciers located to the north-northeast up to about 25,000 years ago

(Fisk, 1944; Esling et al., 1989) (Figure 1). The ancestral Ohio River is interpreted to have abandoned this northern course and migrated to its present-day location about 14,000 years ago, at or near the time of the Maumee Flood on the Tennessee River (Wayne and Zumberge, 1965; Olive, 1980).

Some faults comprising the FAFC are recognizable in DEM images as 6- to 12-mi-long (10- to 20-km) northeast-trending lineaments that coincide with linear valleys, bluffs and drainages (Figure 1). Nelson et al. (2002) suggest that numerous creeks, as well as the ancient path of the Ohio River in southern Illinois, appear deflected across faults within the FAFC. For instance, the ancestral Ohio River valley exhibits about 6 to 9 miles (10 to 15 km) of possible left-lateral deflection across the Lusk Creek fault zone of the FAFC, whereas smaller creeks such as Barnes and Massac Creek follow the northeast-southwest structural grain of the FAFC (Figure 1). Faults associated with the FAFC, however, do not appear to deflect the present-day courses of the Ohio River and Mayfield Creek (Figure 1). Alternatively, the apparent deflection of the Ohio River may be in response to the juxtaposition of different rock types at the fault and differences in resistance to erosion. In this case, the apparent deflection is bedrock-controlled and represents a fault-line escarpment along the Lusk Creek fault zone, and thus the deflection may not be related to recent tectonic activity (J. Nelson, personal communication, 2006).

South of the Ohio River in the elevated terrain of the PGDP, there is little geomorphic expression of prominent northeast-trending lineaments (e.g., linear valleys, drainages and bluffs) similar to those readily observed in southern Illinois (Figure 1). For instance, a digital elevation map (Figure 1) exhibits few northeast-trending lineaments or linear drainage patterns suggestive of structural control. Furthermore, the modern day Ohio River and Mayfield Creek also show no distinct deflection across the southern projection of the FAFC that might be construed as tectonic-related deformation. Drahovzal and Hendricks (1996) performed a comprehensive geomorphic analysis of the region and identified numerous northeast-trending lineaments in the vicinity of the PGDP that are similar in style and orientation, and project toward the FAFC (see their Plate 2). Based on 1:250,000-scale SLAR (synthetic-aperture radar data) imagery, Drahovzal and Hendricks (1996) interpret two lineaments about 800 feet (244 m) northwest and southeast of the margins of the proposed C-746-U landfill (Figure 2). The northwest-bounding SLAR-lineament appears to coincide with a northeast-striking fault previously imaged in geophysical profiles of Woolery and Street (2002), as well as a groundwater contaminant plume within the Tertiary-Quaternary Mounds Gravel. The study by Drahovzal and Hendricks (1996) suggests that some of the SLAR-lineaments coinciding with faults may be of structural origin.

3.0 REGIONAL STRATIGRAPHY

The regional stratigraphy is based on the geologic mapping of the area by Finch, 1967; Olive, 1980 and Nelson et al., 2002 and site specific subsurface studies performed by SAIC (1994 and 2004).

3.1 Pre- Late Quaternary Stratigraphy

The stratigraphic history of the site region is greatly influenced by its position at the northern margin of the Mississippi embayment and the structural control imparted by the Illinois basin, Rough Creek graben, and Reelfoot rift. The regional stratigraphy consists of south-dipping Cretaceous through Tertiary clastic sediments thinning over northwest-dipping Paleozoic bedrock at the northern end of the Mississippi embayment (Nelson et al., 1999). Post-Paleozoic regional stratigraphy includes northwest-dipping Mississippian limestone unconformably overlain by about 300 to 330 feet (92 to 101 m) of south- to southwest-dipping Upper Cretaceous and Tertiary deposits, which in turn are overlain by Quaternary material (Finch, 1967; Olive, 1980) (Figure 5). A generalized stratigraphic column for the region is shown in Figure 6. The Upper Cretaceous deposits are about 200 feet (61 m) thick, and include non-lithified, interbedded fine-grained sand and clay of the McNairy Formation present at about 70 to 80 feet (21 to 24 m) below the ground surface (Woolery and Street, 2002; SAIC, 1994). Stratigraphically above the McNairy Formation is the Porters Creek clay, which is dark gray, slightly to very micaceous clay of Paleocene age. Unconformably overlying the Cretaceous and Paleocene deposits is about 100 feet (30 m) of Plio-Pleistocene sand and gravel that locally are referred to as the Upper and Lower Continental Deposits, The Lower Continental Deposits regionally correlate with the Mounds Gravel and the Upper Continental Deposits largely correlate with the Metropolis Formation in southern Illinois and western Kentucky (Nelson, personal communication, 2005). Based on borehole data south of the proposed landfill, Mounds Gravel unconfomably overlies the McNairy Formation and Porters Creek Clay (SAIC, 2004). At the PGDP facility, Mounds Gravel is defined as a buried paleo-terrace riser trending roughly west to northwest across the southern part of the facility (Phillips, 1992) (Figure 2). Grading into the Mounds Gravel is an approximately 30-foot-thick (9 m) “silt and sand” terrace deposit previously mapped by Finch (1967) and Pryor and Ross (1962), which largely correlates with the Metropolis Formation of southern Illinois (Nelson et al., 1999; John Nelson, personal communication, 2005). The Metropolis Formation is overlain by several packages of late Pleistocene loess deposits as described below.

3.2 Late Quaternary Stratigraphy

The Plio-Pleistocene Metropolis Formation, Pleistocene loess packages, and associated paleosols developed in the loess are less than a few million years old, and thus form the fundamental stratigraphic sequence and marker units of the Holocene faulting investigation. Nelson et al. (2002) describe the Metropolis Formation as a fluvial deposit consisting principally of silt and sand with lesser amounts of clay and chert gravel. The Tennessee, Ohio, Mississippi and Cumberland Rivers are sources of the sediment for the Metropolis Formation (Olive, 1980; Nelson et al., 1999). Nelson et al. (1999) interpret fluvial units in the Metropolis Formation to be aggradation phases of a glacial-interglacial cycle, and buried soils developed within these deposits to represent interglacial phases during the late Pleistocene.

In this part of the central United States, at least three late Pleistocene loess deposits formed as a result of the extensive glaciation and de-glaciation during the late Quaternary overlie the Metropolis Formation. Each loess deposit has a subsequent soil (i.e., "paleosol", or buried soil) developed near the top of the deposit denoting an interglacial period of relative landscape stability (Follmer, 1996; Grimley et al., 2003). The three late Pleistocene loess deposits that have been recognized on a regional scale are thought to have been deposited between approximately 200,000 and 10,000 years ago (200 to 10 ka). Regional models interpret the loess deposits as follows: Loveland Silt (180 to >125 ka), Roxana Silt (55 to 28 ka), and Peoria Loess (25 to 10 ka) (Curry and Follmer, 1992; Leigh, 1994; Follmer, 1996; Grimley et al., 2003; Forman and Pierson,, 2002; Bettis III, et al., 2003). Locally near the PGDP facility, these deposits are as much as 20 feet (6.1 m) thick. If faulting has occurred within the time frame of loess deposition (200 to 10 ka), one or more of the loess units should exhibit deformation.

The Loveland Silt is found stratigraphically below the Roxana Silt and Peoria Loess, along the major rivers of the Midwest (Follmer, 1996; Grimley et al., 2003). It generally is defined as silt, that is strongly mottled in yellow, orange, and gray. It is massive to blocky and commonly sandy, especially near its base, and has the same overall silty texture as the Peoria Loess (Nelson et al., 2002). The Loveland Silt is primarily aeolian in origin and was deposited during the late Illinoian glaciation (marine isotope stage 6), and has an age of about 125 to 180 ka.

The Roxana Silt is regionally defined as a pinkish brown to tan loess and colluvial silt that was deposited throughout much of the central United States during the middle Wisconsin (Follmer, 1996). The lower portion of the Roxana Silt has been interpreted as colluvial in origin, whereas the main body of Roxana

Silt is believed to be loess that originated through deflation of valley-train deposits of the ancient Mississippi River between 55 and 28 ka (Curry and Follmer, 1992; Leigh and Knox, 1993).

The Peoria Loess is yellowish brown to grayish brown and is common throughout the central United States as the youngest surface-mantling loess unit. This unit was derived largely from valley-train deposits between about 25 and 10 ka along the Illinois and Mississippi valleys (Follmer, 1996; Hansel and Johnson, 1996). The Peoria Loess mantles the bluffs and ridges south of the Ohio River and at the proposed C-746-U landfill.

3.3 Regional Paleosols

Paleosols of regional extent developed during the interglacial periods, and in between the three late Pleistocene loess packages. These paleosols provide stratigraphic markers for assessing Holocene faulting at the proposed landfill expansion. The presence of buried paleosols, as well as the soil horizons near the ground surface ("relict soil"), indicates intermittent periods of relative landscape stability during which original deposits are altered by pedogenesis (soil formation; Birkeland, 1986). Development of the soil horizons is a function of five primarily factors: climate, biological activity, relief (topography), parent material and time (Jenny, 1941). Because of these factors, soil-forming (pedogenic) processes acting through geologic time produce soil stratigraphic characteristics that can be used to correlate deposits that have undergone similar depositional and post-depositional histories. Thus, buried paleosols can be correlated over fairly large distances if the soil-formation factors are taken into account, and can be used as local or regional stratigraphic markers to assess the presence or absence of deformation. For this study, paleosols provide the means to estimate deposit age through regional correlation with dated paleosols, and to evaluate fault displacements through correlations of soil horizons across fault zones.

Geologic and pedologic studies in the Midwestern United States have identified several prominent paleosols developed in Quaternary deposits. From oldest to youngest, the paleosols include the: (1) Yarmouth Geosol, which developed in the lower part of the Metropolis Formation and upper part of Mounds Gravel (Esling et al., 1989; Grimley et al., 2003); (2) Sangamon Geosol, which developed into the upper part of the Metropolis Formation and the Loveland Silt; (3) Farmdale Geosol, which formed in the Roxana Silt, and the (4) modern-day soil profile developed in the Peoria Loess. The Yarmouth Geosol formed over an extensive period of time and is broadly correlated with Marine Isotope Stages (MIS) 7 to 11, the Crowley's Ridge silt (Grimley et al., 2003), and parts of the Metropolis Formation. In most places, the Loveland Silt is modified by formation of the Sangamon Geosol that developed during the Sangamon-time interval from about 65 to 125 ka (Grimley et al., 2003; Forman and Pierson, 2002). The Sangamon Geosol is characterized by a thick solum, an increase in illuviated clay with depth that is derived from the loess parent material, clay films, red hue (7.5YR or 5YR hues), prominent clay seams along prismatic and angular blocky peds, and well-developed zones of manganese oxide development. Development of the Sangamon Geosol ended during the deposition of the Roxana Silt upon which the Farmdale Geosol is developed. The Farmdale Geosol is considered to have formed in a cool climate over a period of about 3,000 to 5,000 years between 30 and 25 ka before the last glaciation (Follmer, 1983; Forman and Pierson, 2002).

The Peoria Loess overlies the Roxana Silt and is estimated to be between 25 and 10 ka in age (Forman and Pierson, 2002). Soils developed in the Peoria Loess and mapped previously at the C-746-U landfill are predominantly silt loams with moderately developed B-horizons that began developing about 12,000 years ago. The major soil series developed in the Peoria Loess at the site include the Calloway, Henry and Grenada silt loams (U.S. Department of Agriculture, 1976) that typically form on level to gently sloping hillsides. The surface soils consist of a moderately developed fragipan, and a relatively compact, unaltered silty clay loam that ranges from 66 cm (below the ground surface) to 125 cm in depth.

4.0 PREVIOUS SITE-SPECIFIC C-746-U LANDFILL GEOLOGIC STUDIES

An initial geologic and geotechnical study for the C-746-U landfill and subsequent seismic reflection survey provide valuable information on site stratigraphy and inferred faults lying beneath the site. The following section provides a summary of the findings of the previous investigations performed at the landfill, and Woolery's (personal communication, 2005) re-interpretation of seismic felecion data previously acquired at the site.

4.1 SAIC (1994)

A geotechnical and geologic investigation performed by SAIC (1994) prior to construction of the existing C-746-U landfill included completion of 27 shallow (12 to 32 ft; 3 to 9.8 m) and 5 deep (85 to 90 ft; 26 to 27 m) exploratory borings across a former low ridge (Plate 1). Pre-development maps show the former site topography consisted of a relatively narrow northeast-trending ridge bounded by northeast trending creeks (e.g., Little Bayou Creek) and dissected by east and west-trending swales (SAIC, 1994) (Plate 1). The swales drain toward Bayou and Little Bayou Creeks located to the west and east of the site, respectively (Figure 5). The Bayou and Little Bayou Creeks drain to the Ohio River located north of the site.

Geotechnical borehole information indicate that the upper 30 feet (9 m) of stratigraphy at the site coarsens with depth, and includes a shallow (approx. upper 15 feet [4.6 m]) surficial package of loess directly overlying massive silt and clay (approx. 15 to 30 feet [4.6 to 9 m]) with occasional interbeds of silty sand to clayey sand (inferred as Metropolis Formation) (Figure 7). Particle-size data from the loess and upper part of the Metropolis Formation, within 5 to 15 feet (1.5 to 4.6 m) of the ground surface, indicate the clay fraction increases with depth (see Tables E5 and E6 of SAIC, 1994). This increase in clay likely represents, in part, the presence of the Sangamon Geosol that overprints much of the upper part of the Metropolis Formation. In addition, grain size analyses (see Figure 9 of SAIC, 1994) indicate the presence of two relatively continuous sandy units between 15 and 18 feet (4.6 and 5.5 m) below the ground surface (bgs) (i.e., contains as much as 20-25% sand) and 22 and 25 feet (6.7 and 7.6 m) bgs (i.e., contains as much as 60% sand) that are part of the Metropolis Formation (Figure 7). These paleosols and sandy units, in part, are marker horizons by which to assess tectonic-related deformation for the fault hazard investigation (this study).

4.2 Blackhawk Seismic Reflection Survey (2003)

Because of the recent studies that identified faulting at and near the vicinity of the PGDP (SAIC, 2004; Woolery and Street, 2002), the Commonwealth of Kentucky requested that a fault investigation be conducted at the proposed C-746-U landfill expansion. Consequently, a high-resolution horizontal shear wave (S-wave) seismic reflection survey was acquired at the C-746-U landfill by Blackhawk GeoSciences (Blackhawk, 2003). The purpose of the study was to identify potential subsurface anomalies suggestive of young and near-surface faulting, and to intersect faults striking predominantly northeast through the existing and proposed C-746-U landfill site. The survey consisted of two S-wave lines (SL-1 and SL-2) oriented parallel to the present-day northern and eastern boundaries of the landfill (Plate 1). Seismic line SL-1 is oriented north-south and is about 1,800 feet (550 m) long. Seismic line S-2, oriented east-west, is about 1,400 feet (427 m) long.

Blackhawk's (2003) interpretation of the seismic data includes identification of two clearly discernable buried reflectors correlating with the top of the local hydrologic unit known as the Regional Groundwater Aquifer (RGA; this unit is regionally correlated with the Mounds Gravel) at about 70 to 40 feet (21 to 12 m) bgs and the top of the McNairy Formation at about 60 to 80 feet (18 to 24 m) bgs (Figures 8 and 9). The reflector between 30 and 40 feet (9 and 12 m) bgs is interpreted as the top of a coarse-grained unit that presumably lies within the upper part of the Mounds Gravel or lower part of the Metropolis Formation. Based on discontinuities of these reflectors and incoherence patterns in the seismic data, Blackhawk (2003) interpreted two near-vertical faults, designated Fault 1 and Fault 2 (Figures 8 and 9). These faults are inferred to have northeasterly strikes with down-to-the-northwest vertical separation across the northern and central part of the C-746-U landfill footprint (Plate 1). Blackhawk (2003) shows displacements of the McNairy Formation by as much as 30 feet (9 m) and of a distinct overlying reflector within the Metropolis Formation or Mounds Gravel by as much as 20 feet (6.1 m). Blackhawk (2003) also interprets faulting within the older units (Metropolis Formation and Mounds Gravel), and suggests that faulting may extend within 15 to 20 feet (4.6 to 6.1 m) of the ground surface; however, the age of the shallowest units where deformation is interpreted could not be determined given the resolution of the data.

4.3 Alternative Interpretation of Seismic Lines SL-1 and SL-2

Prior to this study, SAIC (1994) borehole data and Blackhawk (2003) seismic lines provided the best subsurface information for delineating the locations and styles of possible deformation in the investigation area. These data are used in defining the target areas for detailed borehole arrays described in section 5.0 below. As part of this fault hazard investigation, Dr. Ed Woolery of the University of Kentucky provided an independent review of Blackhawk (2003) seismic lines SL-1 and SL-2 (Woolery, personal communication, 2005). Based on offset reflectors, abrupt terminations of strong reflection signals, residual diffraction patterns, abrupt changes in reflection dips, and associated folds the re-analysis suggests a more complex fault zone than previously interpreted by Blackhawk (2003). Woolery finds numerous normal and reverse faults, as well as warped and folded stratigraphy that collectively suggest a transpressional style of deformation (Figures 8 and 9). In general, the seismic lines exhibit episodic tectonic-related deformation that extends above the Paleozoic bedrock into overlying unconsolidated Quaternary deposits and close to the base of the inferred loess deposits. Deformation zones identified from the interpretation of the seismic lines are discussed below.

4.3.1 Alternative Interpretations of Seismic Line SL-1

In line SL-1, three primary zones of deformation (DZ1-1 to DZ1-3) are interpreted. The deformation zones of Woolery (personal communication, 2005) are shown in Figures 8 and 9.

4.3.1.1 Deformation Zone DZ1-1

Deformation zone DZ1-1 is about 260 feet (79 m) wide and lies along the southern part of line SL-1 between shot points UKK-1-100 to-235 (Figure 8). Blackhawk (2003) did not interpret faulting in this area. The zone of deformation is characterized by a series of steep, north- and south-dipping faults that exhibit both normal and reverse displacement. The northern margin of the deformation zone is bordered by a prominent zone of incoherent reflectors truncated near shot point UKK-1-235. Faults within deformation zone DZ1-1 have inferred displacements of as much as 25 feet (7.6 m) within the Mounds Gravel, whereas vertical displacements are less than about 3 feet (0.9 m) across disrupted reflectors representing strata likely within the Metropolis Formation.

4.3.1.2 Deformation Zone DZ1-2

Deformation zone DZ1-2 is relatively narrow (160-ft-wide;49-m-wide) and is between shot points UKK-1-350 to-430 (Figure 8). This zone is roughly coincident with Fault 2 of Blackhawk (2003), and is defined by a steep, north-dipping fault that extends upsection into the Metropolis Formation. Directly south of the fault is a region of incoherent reflectors that does not permit the interpretation of a readily identifiable or laterally continuous reflectors for assessing fault location.

4.3.1.3 Deformation Zone DZ1-3

Deformation zone DZ1-3 is about 120 feet (36.6 m) wide and is located at the northern end of line SL-1 (Figure 8). This portion of the seismic line is characterized by a loss of coherency between shot points UKK-1-785 to-905 (Figure 8). Although Blackhawk (2003) did not interpret faulting along this zone, Woolery (personal communication, 2005) identified two boundary faults that exhibit an apparent southside-down vertical separation. The northernmost boundary fault is interpreted to extend into the Metropolis Formation with a total vertical separation of about 2 feet (0.61 m). The overall structural style of deformation interpreted across deformation zone DZ1-3 is extensional. Because this area of the proposed landfill expansion lies within a forested region it was not investigated as part of the surface-fault rupture investigation.

4.3.2 Alternative Interpretations of Seismic Line SL-2

Re-interpretation of seismic line SL-2 suggests the presence of two primary deformation zones (DZ2-1 and DZ2-2) which respectively coincide with Faults 1 and 2 of Blackhawk (2003) (Figure 9).

4.3.2.1 Deformation Zone DZ2-1

Deformation zone DZ2-1 lies along the central part of seismic line SL-2 and is about 90 feet (27 m) wide and is located between shot points UKK-2-315 to-360 (Figure 9). Three relatively high-angle fault strands are interpreted as offsetting shallow reflectors within the Mounds Gravel and Metropolis Formation. The primary fault, which is located near shot point UKK-2-360, dips southerly and branches upsection into a half-flower structure accompanied by two north-dipping faults that offset the Metropolis Formation. Deformation zone DZ2-1 corresponds with Fault 1 of Blackhawk (2003)

4.3.2.2 Deformation Zone DZ2-2

Deformation zone DZ2-2 lies along the eastern part of seismic line SL-2 and is about 420 feet (128 m) wide and is located between shot points UKK-2-509 to 719 (Figure 9). This deformation zone represents the most prominent anomaly of the seismic reflection survey. Four possible high-angle north and south-dipping fault strands exhibiting both normal and reverse displacement are interpreted across deformation zone DZ2-2. The Mounds Gravel is interpreted as being displaced as much as 10 feet (3.0 m), whereas seismic reflections believed to be in the Metropolis Formation exhibit vertical displacements up to 2 feet 0.61 m). The pattern and style of deformation interpreted along this section of line SL-2 is suggestive of a “positive” flower structure, and thus may represent transpressional deformation. Deformation zone DZ2-2 coincides with Fault 2 of Blackhawk (2003).

5.0 ANALYTICAL APPROACH AND METHODS

The primary objective of this fault hazard evaluation of the proposed the C-746-U landfill expansion is to intersect shallow deposits and soil horizons, to assess their age and lateral continuity, and to identify the absence or presence of fault-related vertical displacements. A total of 86 DPT cores were collected at variable spacings along parts of seismic lines SL-1 and SL-2 to specifically target possible deformation zones identified by Blackhawk (2003), and Woolery (personal communication, 2005) (Plate 1). In addition, a total of 12 optically stimulated luminescence samples were collected from the cores to provide age estimates of the shallow loess deposits by which to assess active faulting (i.e., within the last 11,000 years; Holocene Epoch; see section 5. 3). Our approach was to span these zones with initial borehole spacings of 40 feet (12.2 m), followed by smaller intervals of 20 and 10 feet (6.1 and 3.0 m) in areas containing possible fault-related features interpreted from seismic data, or inferred from preliminary cross-sections developed from initial boreholes. The DPT core locations are indexed to the shotpoint numbers along seismic lines SL-1 and SL-2, and are designated according to the previous shotpoint designations.

The elevations along the two transects range from approximately 367 feet (112 m) above mean sea level (msl) at the eastern end of seismic line SL-1, to 372 feet (113 m) above msl at the southern end of seismic line SL-2 (Plate 1). The borehole transects traverse an area that is readily accessible, and currently is vegetated with grasses or covered with gravel. Both transects are outside of the C-746-U landfill security fence. The locations of the direct push cores and geophysical profiles are provided in Plate 1. The areas of detailed subsurface studies do not span the entire region of interpreted faulting by Woolery (personal communication, 2005), although the investigation intersects zones of deformation considered to be the most prominent and distinct on the interpreted seismic reflection profiles.

Miller Drilling Company collected 86 direct push technology (DPT) Geoprobe cores along the two transects to explore subsurface conditions at the site. The cores were collected as continuous cores. Four of the 86 DPT cores were collected in light-sensitive sample liners, placed within a PVC pipe and specially handled for optical stimulated luminescence (OSL) analysis. A Geoprobe, a hydraulically-powered, soil probing machine that utilizes static force and percussion to advance small-diameter soil sampling tubes collected the cores. All the DPT cores extended to a depth of 30 feet (9 m) and consist of approximately 1 and 11/16-inch-diameter samples within six (6), 5-foot-long (1.5 m) sections at each borehole location. The core samplers extended into undisturbed stratigraphy below the base of the sampler by static force from the Geoprobe machine. Clear, thin-walled plastic liners within the Geoprobe sampler tubes preserved the sediment cores. The sampler tubes were labeled, sealed and placed in wooden core boxes for shipment to the Kentucky Geological Survey (KGS) core facility in Lexington. Following the collection and labeling of each DPT core, the entire depth of each borehole was sealed with a bentonite/Portland cement grout mix. Following temporary storage of the cores on site, the WLA staff geologist and SAIC field operations manager containerized and padded the cores to maintain their integrity for shipment to the KGS core facility. The field staff followed standard chain-of-custody (COC) procedures throughout the sampling and transportation process of the cores. KGS project personnel at the KGS core library checked the cores and COC documents prior to accepting the cores. There were no inconsistencies encountered during transportation of the cores and chain-of-custody procedures.

Project geologists, scraped clean, and described the 30-ft-long (9 m) continuous cores in detail to identify stratigraphic marker horizons, buried soils and any concealed evidence of faulting. The project geologists placed sets of five to six DPT cores side-by-side and in sequential order for detailed characterization and direct correlation of soil and deposit stratigraphy between cores. Using the Unified Soil Classification System and standard geologic and pedologic observations (see site work plan dated June 21, 2005) geologists logged the cores. This logging procedure produced preliminary geologic cross-sections based on the DPT data and allowed confirmation of laterally continuous horizontal strata among adjacent borings.

5.1 Uncertainty Estimation

Geologic cross sections developed from the DPT data incorporate the uncertainty in the location of stratigraphic boundaries between the primary geologic units at the site. In estimating the elevations of the basal contacts of the stratigraphic horizons, six sources of uncertainty are considered: (1) actual stratigraphic variability; (2) mechanical error in measurement (assumed to be zero); (3) elevation error in survey of monuments; (4) core compression and/or recovery; (5) contact correlation and interpretation; and (6) presence of inclined basal contacts. The natural stratigraphic variability (#1) of each basal contact is assumed to be adequately represented in the 86 borehole samples. Mechanical uncertainty (#2) is considered minimal, if present at all, because the depth of each contact was measured numerous times and/or reviewed by several geologists during our internal review process. Uncertainty in elevation (#3) from the licensed survey is considered to be within the nearest 0.1 foot (0.03 m) horizontally and 0.01 foot (0.003 m) vertically, and thus is considered negligible in this analysis. Of these potential contributors to the uncertainty in the basal contact elevation error, three types of uncertainty (#4 to #6) need to be critically evaluated.

Thus, the sources of basal contact elevation error that need to be addressed include: (#4) core compression and/or recovery, (#5) contact correlation and interpretation (i.e., distinct vs. gradational), and (#6) the presence of inclined basal contacts. The methods for determining these sources of uncertainty are described below. Core compression and recovery (#4) was documented for every core in this study during core collection and core analysis phases. Core compression often accounts for most, if not all, of the "missing" core where recovery was less than 100% for each 5-foot (1.5 m) core sample. Since the DPT method obtains cores by pushing the sampling tube into the ground, it is not uncommon for some of the soils to compress as they enter the sample tube. For example, during a 5-ft (1.5 m) sample run, only 4-ft (1.2 m) of core may be recovered from the sample tube with the 1-ft (0.3 m) of "missing core" representing a 20% compression of the 5-ft (1.5 m) soil due to sampling method. For each basal contact, we recorded the amount of compression (depth measured vs. amount of core recovered) and used this value as the range of uncertainty for any basal contact encountered within that 5-foot (1.5 m) sample interval. Compression and recovery uncertainty values ranged from 0.1 feet (0.03 m) to as much as 1.6 feet (0.5 m). The uncertainty contact correlation and evaluation (#5) was determined to estimate the geologist's confidence in choosing each basal contact. Essentially this value is a measure of how difficult it was to identify each contact. This uncertainty (#5) was evaluated by taking an estimate independently from each geologist that logged the core, and taking the average uncertainty value for each basal contact. The average uncertainty values of the basal contact are listed in Table 1. Significantly non-horizontal or inclined basal contacts (#6) were evaluated for selected basal contacts only. Based on core logging, the basal contact of unit 5.2 is erosional, and the only significantly non-horizontal (i.e., steeply inclined) contact. There were 5 significantly non-horizontal basal contacts with uncertainties ranging between 0.4 and 0.5 feet (0.12 and 0.15 m).

Table 1. Average Uncertainty in Contact Correlation by Stratigraphic Unit

Basal Contact	Uncertainty (feet)
Base of Upper Peoria, unit 1	0.6
Base of Lower Peoria, unit 2	0.4
Base of Roxana Silt, unit 3	0.4
Base of Unnamed Intermediate Loess, unit 4	0.3
Base of Metropolis, unit 5.1	0.5
Base of Metropolis, unit 5.2	0.4

Overall, the greatest source of uncertainty in estimating the basal contact elevation is from (#4) core compression, and (#5) a lack of a distinct basal contact. For developing the geologic cross sections, the largest uncertainty of those described above (#4, #5, & #6) was selected as the range in possible uncertainty. For example, if 1 foot (0.3 m) of core compression (#4) represented the largest error for a basal contact, then an error of 0.5 feet (0.15 m) was placed on either side of the noted basal contact elevation. This is represented by an error bar at each basal contact for each DPT core on the geologic cross-sections discussed in Section 6.0.

5.2 Estimated Ages of Deposits

The assessment of fault activity requires an understanding of the Quaternary and depositional history of the site area, and a means to estimate the age of stratigraphic deposits or bedrock units. In assessing the age of surficial deposits at the C-746-U landfill, we use: (1) stratigraphic position and cross-cutting stratigraphic relations; (2) radiocarbon analyses of eight charcoal-like fragments collected from near-surface deposits encountered in the DPT cores; and (3) optical stimulated luminescence (OSL) analyses of 12 sediment samples collected from DPT cores. Pedogenic development also provided a means to assess relative ages of deposits among the core samples, and to obtain correlative ages by comparison with well-dated soil chronosequences in the region (i.e., Farmdale vs. Sangamon Geosols).

During the logging procedure, material resembling charcoal was noted on log forms and subsequently collected for radiocarbon analysis. The radiocarbon method is applicable primarily in dating organic material formed from photosynthetically fixed carbon within the last 50,000 to 60,000 years (Trumbore, 1998). The dimensions and angularity of each charcoal sample, as well as interpretation of the type of carbon extracted (e.g., detrital charcoal, wood, stick, seed, root, etc.) were noted on a sample log form. Individual carbon samples were wrapped securely in aluminum foil, which was labeled with a sample designation, collection date, project description, and placed in a sealed plastic bag. Individual charcoal samples were further screened for likelihood of containing carbon by analyzing the samples under a microscope. Out of a total of 46 samples, eight (8) possible charcoal samples were selected and submitted to Beta Analytic, Inc. (Miami, Florida) for radiocarbon analysis using the accelerator mass spectrometry (AMS) technique. The very small radiocarbon samples (between 1.3 and 189 milligrams) were treated with acid and base washes, followed by combustion prior to analysis. Following the combustion phase, Beta Analytic noted that there was not enough carbon available for the AMS technique, or the resultant material presumed to be charcoal was primarily iron or magnesium oxides comprised of fine-grained silt and clay particles. As a result, none of the eight (8) samples was adequate for radiometric analyses. The age estimates of the deposits encountered at the site are based on optically stimulated luminescence (OSL) samples derived from loess units, as well as correlative age estimates based on relative soil development.

Twelve (12) OSL samples were collected from the DPT cores and submitted to the University of Illinois, Chicago (UIC) for analyses by Dr. Steve Forman, director of the UIC OSL laboratory. The application of the OSL method closely parallels the application of carbon-14 dating and provides a complimentary dating range spanning a few centuries to limits in the range of 2 to 10 percent. Cores collected in light-sensitive sleeves were transported to UIC, where WLA opened and logged the core in the UIC OSL laboratory. Each core submitted for analysis was collected adjacent to a “pair” core that was logged in detail at the KGS library. Both cores for each OSL analysis were shipped from KGS and re-opened at UIC, and used as a guide for evaluating stratigraphic and pedologic boundaries during the OSL analysis. Samples identified for OSL analysis in both the light-sensitive and regular cores were selected based on proximity to stratigraphic and pedogenic boundaries, and the preferred absence of features related to bioturbation and other pedogenic processes. The results of the OSL analyses are presented in Table 2, and a description of the OSL analytical methods can be found in Forman and Pierson (2002).

5.3 Survey of Geoprobe Locations

Prior to drilling, Dummer Surveyors surveyed and marked the core locations with labeled wooden stakes. The proposed DPT core locations coincided with shot point designations from the Blackhawk (2003) seismic lines SL-1 and SL-2. Dummer Surveyors also preformed a civil survey of the final borehole locations and elevations following the drilling program to provide the location and elevation of the DPT boreholes. The elevations of each borehole are used for stratigraphic correlation among boreholes along the two transects. Elevation measurements are within the nearest 0.1 foot (0.03 m) horizontally and 0.01 foot (0.003 m) vertically, and are tied to the PGDP coordinate system and U.S. Coast and Geodetic Survey monuments.

6.0 EVALUATION OF LATE PLEISTOCENE STRATIGRAPHY

The DPT cores collected for this surface fault rupture investigation exhibit seven primary stratigraphic and pedologic late Pleistocene horizons. The late Pleistocene stratigraphic deposits consist of laterally continuous fining upward fluvial packages overlain by loess. The age of the surficial deposits encountered in the DPT cores are as much as 75.5 ka. Geologic cross-sections depicting subsurface conditions underlying the western and northern margins of the landfill provide the basis for assessing the absence or presence of Holocene (within the last 11,000 years) faulting at the site. From the cross-sections, as many as four (4) folds or warps, and 21 features with representative elevation changes across stratigraphic and/or pedologic boundaries are inferred from the Geoprobe data. However, no actual fault surfaces, slickensides, or fault gouge was observed in any of the cores; interpretations of possible fault displacements are based primarily on elevation changes among the various DPT core locations. These elevation changes can also be explained by original topographic variability and/or erosional contacts between strata. The estimated amount and style of vertical separation of the features are summarized in Tables 3 and 4 and discussed in Section 6.2. Most of the anomalous features are limited to horizons within the Metropolis Formation and unnamed intermediate loess, however it is possible that several of the fault-like features extend upward close to the base of the Peoria Loess. The near-surface stratigraphy encountered in the DPT cores, and possible near-surface structural features interpreted from the geologic cross section, are discussed in the following sections.

6.1 Near-Surface Stratigraphy at the C-746-U Landfill

Near-surface stratigraphy at the site is based on a review of previously drilled geotechnical boreholes and seismic reflection profiles, coupled with detailed descriptions of 86 DPT cores collected as part of this fault hazard study. At least seven distinct stratigraphic horizons (units 1 to 4 and units 5.1 to 5.3) are recognized in the upper 30 feet (9.1 m) of material at the C-746-U landfill. The upper three horizons are generally nearly flat-lying and mantle pre-existing topography. The lower horizons occasionally have subtle to abrupt undulations of stratigraphic contacts that reflect fluvial depositional processes. Between depths of about 19 and 30 feet (5.8 and 9.1 m) bgs, three stratigraphic horizons (units 5.1 to 5.3) are present within the Metropolis Formation. This part of the Metropolis Formation (approximately 25 to 30 feet [17.6 to 9.1 m] bgs) is composed primarily of interbeds of coarse-grained sand and gravel with channel-like morphology and cut and fill structures. These deposits were also interpreted at a similar depth in the geotechnical boreholes for the design of the landfill (SAIC, 1994) (Figure 7). The Metropolis

Formation fines upsection, between about 25 and 19 feet (7.6 and 5.8 m), and consists of strongly mottled clay, silt and fine-grained sand with discontinuous interbeds of sand and sandy gravel and likely mixes, in part, with the Loveland Silt. The Sangamon Geosol overprints the upper section of the Metropolis Formation as prominent subvertical clay seams and orange and red mottles. Directly overlying the Metropolis Formation is a 15-to 19-ft-thick (4.6-to 5.8-m-thick) loess package that includes an unnamed loess, the Roxana Silt and the Peoria loess. As noted below, the Peoria Loess is herein subdivided informally into lower and upper parts.

6.1.1 Upper Peoria Loess (unit 1)

The uppermost surficial deposit in the study area is the Peoria Loess. At the site, Peoria Loess is subdivided into two units (units 1 and 2) based on the presence of a weak paleosol in the middle of the loess package. The Upper Peoria Loess (unit 1) is about 6 feet (1.8 m) thick and is characterized as a brown (10YR5/3) to yellowish brown (10YR5/8) clayey silt (up to 15% clay) to clean silt with minor traces of clay. In general, unit 1 is massive and speckled (3-5%) with small (<3mm) angular to sub-rounded blackish nodules of iron-manganese oxyhydroxides. Some cores have poorly developed brown-orange iron-oxide zones defined as mottles and fine nodules. The lower boundary of unit 1 is distinct when well expressed, but is often diffuse to gradual, because of bioturbation, compression from DPT sampling, or the poor expression of an underlying paleosol developed in the Lower Peoria Loess (unit 2). OSL dating of unit 1 yields a range in age between 25.2 and 15.4 ka, consistent with a Peoria Loess age (Table 2). As noted in Section 3.0, the Peoria Loess is approximately 12 to 25 ka (Forman and Pierson, 2002, Grimley et al., 2003).

The Upper Peoria Loess is overprinted by “modern” soil that began developing about 12 ka after the cessation of loess deposition (Forman and Pierson, 2002; Grimley et al., 2003). The soil consists of a thin A-horizon with minor organic accumulation, and a distinct whitish silt-rich E-horizon present at about 1 to 2 feet (0.3 to 0.6 m) bgs. Clay content increases below the E-horizon to as much as 15% where the loess becomes mottled at about 2 to 4 feet (0.6 to 1.2 m) bgs. The C-soil horizon is noted by the decrease in clay content, relatively clean, massive silt with little to no mottling.

6.1.2 Lower Peoria Loess (unit 2)

The Lower Peoria Loess, unit 2, is generally about 3 feet (0.9 m) thick, and the top of the unit is between 5.0 to 9.0 feet (1.5 to 2.7 m) below the ground surface. The Lower Peoria Loess is a brownish yellow

(10YR6/6) to yellowish brown (10YR 5/4-5/8) silt to clayey silt. The upper portion of the loess is weakly to moderately clay-rich and is interpreted to represent a slight illuvial clay accumulation. The upper portion of unit 2 has a similar texture and color to the Upper Peoria Loess (unit 1), but is clearly distinct from unit 1 due to the presence of discontinuous and subhorizontal whitish to light yellow silt laminae. A review of literature regarding the base of the Peoria Loess indicates that these discontinuous laminae are interpreted as mixing or welding from bioturbation and colluvial processes with the underlying Roxana Silt (L. Follmer, personal communication, 2005). With the exception of these laminae, unit 2 generally is massive, moist and soft and compresses readily with the DPT sampling technique. Unit 2 mimics present-day topography similar to unit 1 and generally is horizontal across much of the site explored. The basal contact of unit 2 is generally defined by a relatively distinct clean silt with laminae overlying a more clay-rich silt with abundant relict root casts and mottling. On the basis of OSL dating, the age of unit 2 ranges between approximately 30.9 to 21.8 ka (Table 2), consistent with the basal age of Peoria Loess and welding with Roxana Silt (unit 3).

A weakly developed soil horizon defines the top of unit 2. The soil horizon is identified in the cores based on the presence of subtle to moderate iron-manganese oxyhydroxides developed within the upper 0.5 feet (0.15 m) of the unit. As the oxyhydroxides decrease down section to less than 5% nodules, there is a corresponding subtle increase in clay content. This paleosol contains few randomly distributed pedogenic interfaces (e.g. fractures) lined with whitish silt.

6.1.3 Roxana Silt (unit 3)

In the study area, the Roxana Silt, unit 3, conformably overlies unit 4 (unnamed intermediate loess) and ranges from about 1 to 2.5 feet (0.3 to 0.76 m) in thickness. The Roxana Silt of the study area lacks the more distinct pinkish hue often reported elsewhere in the central United States (Grimley et al., 2003). Unit 3 consists of a yellowish brown (10YR5/4) to pale brown (10YR6/3) silt with clay and silty clay and contains distinct, discontinuous, yellowish-white thin laminations. Unit 3 also contains prominent clay films along well-developed pedogenic interfaces, a significant clay content compared to overlying loess packages, extensive mottling and well-developed, clay-filled root casts. The basal contact of unit 3 is about 10 to 11.5 feet (3.0 to 3.5 m) below the ground surface. The basal contact generally is defined as distinct and is marked by a thinly laminated yellowish-brown silt with little to no manganese-oxides. It overlies a darker brown to grayish-brown silty clay (interpreted as a buried paleosol) that denotes the top of unit 4 (unnamed intermediate loess). Based on the OSL analyses, the age of unit 3 ranges from 32.1 to

50.7 ka (Table 2). This age range is consistent with reported ages for the Roxana Silt in the central United States (Grimley et al., 2003).

The Farmdale Geosol and associated mottling and clay development overprints and obscures much of the massive nature of unit 3. The upper part of the Farmdale Geosol is marked by the concentration of fine- to medium-sized iron and manganese oxyhydroxide (5-10%) nodules near the upper contact of unit 3. Down section the soil profile contains prominent dark gray subvertical clay seams filling pedogenic interfaces (clay films) and root casts with zones of prominent oxidation along the seams. The Farmdale Geosol exhibits extensive mottling and moderate clay film development in these DPT cores.

6.1.4 Unnamed Intermediate Loess (unit 4)

Within the study area, unit 4 ranges in thickness from 5.0 to 7.0 feet (1.5 to 2.1 m), and is defined as a yellowish brown (10YR5/6) or light brownish yellow (10YR6/4) to brown (10YR5/3) silty clay with thinly laminated silt interbeds. Although relict bedding is partly preserved in the unit, much of it is destroyed by soil forming processes responsible for the well-developed unnamed paleosols present throughout unit 4. The upper part of the unit is marked by a high clay content and manganese oxide staining and nodule development associated with the paleosol. Subvertical grayish clay-rich seams are pervasive throughout the unit and cross-cutting softer yellowish-brown silty clay to clayey silt. In some cores, a second zone of manganese staining and nodules occur about a foot (0.3 m) below the upper contact with unit 3, and are randomly distributed throughout the unit as fine roundish nodules or grains. Unit 4 is strongly mottled, generally moist and soft (silt) to stiff (clay). The basal contact, between 15 to 19 feet (4.6 to 5.8 m) bgs, is generally distinct and characterized by a distinct, massive silty to silty sand horizon with laminations and/or zones of mixing that directly overlie a darker gray clay-rich unit (interpreted as a buried paleosol possibly related to the Sangamon Geosol). Based on two OSL dates yielded from sediment samples collected at 12.1 to 12.3 feet (3.7 to 3.8 m) and 13.1 to 13.4 feet (4.0 to 4.1 m) in DPT UKK-2-544, the age of the central part of this unit ranges between 53.6 and 75.5 ka (Table 2) suggesting an intermediate loess unit exists directly below Roxana Silt and presumably above the Loveland Silt. The Loveland Silt is reported to be older than 120,000 years (Grimley et al., 2003). The basal age of unit 4 is unknown, and therefore may be more representative of Loveland Silt.

6.1.5 Metropolis Formation (units 5.1 to 5.3)

The Metropolis Formation, considered to be Pleistocene in age, consists of a complex fluvial sequence of clay, silt and sand with some gravel that occurs at about 15 to 19 feet (4.6 to 5.8 m) bgs and extends as deep as 30 feet (9.1 m) bgs (maximum depth explored). Based on the DPT cores, the Metropolis Formation is subdivided into three fluvial subunits (units 5.1 to 5.3) based on textural variations and a general fining-upward sequence observed within each unit. The Metropolis Formation encountered in the cores generally represents an upward-fining fluvial sequence that has been overprinted by multiple paleosols. The upper part is silty and has properties similar to the Loveland Silt (>120,000 years), thus the exact boundary between these stratigraphic boundaries is unclear and may lie within unit 5.1.

6.1.5.1 Metropolis Formation-unit 5.1

Unit 5.1 of the Metropolis Formation is generally about 5 feet (1.5 m) thick. The unit is defined as a light brownish gray (10YR6/2) to grayish brown (10YR5/2) clay to silty clay, which grades down section to a gray (10YR5/1) to light grayish brown (10YR6/2), or grayish brown (10YR5/2) clay with silty to sandy interbeds. The upper part of unit 5.1 is generally massive with occasional faint laminations of silt, which may be representative of the Loveland Silt. Vertical dark blue grey clay seams are extensive within the upper 2 feet (0.61 m) of the deposit and interpreted to be filled root casts within the Sangamon Geosol. The lower part of the unit generally contains thin interbeds of sandy silt, silty sand, silt and clay. Iron-manganese oxyhydroxide staining in unit 5.1 is minor and consists of mottling in the upper part of the unit. The basal contact is distinct and varies between 23 and 30 feet (7.0 and 9.1 m) deep. Based on the age of the overlying loess deposits, the estimated age of the upper part of this unit is believed to be close to the age of the Loveland Silt (i.e., 120 to 180 ka).

6.1.5.2 Metropolis Formation-unit 5.2

Within the study area, unit 5.2 of the Metropolis Formation consists of a reddish yellow (7.5YR6/8 to 6/6) to a strong brown (7.5YR5/8) sandy clay or clayey sand (60 to 70% sand) with clay interbeds. Compared to the overlying clay-rich unit 5.1, this unit is composed of a greater percentage of silt, sand and gravel, and characterized by more pronounced iron oxide staining. The upper part of unit 5.2 often contains thin clay interbeds about a foot (0.3 m) below its upper contact, suggesting the presence of a separate fining-upward sequence. Unit 5.2 often occurs below a depth of 26 to 29 feet (7.9 to 8.8 m), and occasionally extends below the depth of exploration. Unit 5.2 is moist to very moist, soft, stiff to hard, with little or no iron-manganese oxyhydroxide staining. The lower portion of the unit is up to 2 feet (0.61 m) thick and often fines upward into a silt or clay.

6.1.5.3 Metropolis Formation-unit 5.3

Unit 5.3 is a bedded, brown (7.5YR5/4) to strong brown (7.5YR5/8), fine- to medium-grained sand and gravel with silt and some reddish yellow (7.5YR6/8) clay laminations. This unit is moist and dense with a distinct orange sand and clay-rich laminae, and often is stained orange-brown. Minor, blue-grey clay subvertical seams that delineate ancient rootcasts or pedogenic clay seams are present throughout the unit. Iron and manganese oxyhydroxide staining is absent or weakly expressed. The base of this unit extends below the depth of subsurface exploration.

6.2 Possible Zones of Near-Surface Deformation

The geologic cross sections prepared from the DPT cores illustrate the lateral continuity of several distinct lithologic loess strata and soil horizons, as well as older fluvial strata, that lie beneath the C-746-U landfill (Plates 2 and 3). These strata and paleosols can be used as strain gauges for assessing: (1) Faults 1 and 2 of Blackhawk (2003), and (2) zones of deformation (e.g., warping, folding and faulting) interpreted from the re-evaluation of Blackhawk (2003) seismic reflection lines SL-1 and SL-2 (Woolery, personal communication, 2005). During the interpretation of the cross sections, anomalous features possibly related to faulting or folding were evaluated with respect to regional seismotectonic models that hypothesize Quaternary faulting along northeast-trending structures (see Section 2.2) (Wheeler, 1997; Nelson et al., 1999; McBride et al., 2002). The long-term deformation pattern of strata beneath the C-746-U landfill is constrained by stratigraphic continuity of the loess and fluvial deposits, and the soils developed in these deposits. The OSL data and regional stratigraphic correlations show that the material encountered is late to middle Pleistocene in age. Because no Holocene deposits are present at the site, any feature interpreted as displacing the Peoria Loess (units 1 and 2 dated between 15.4 and 30.9 ka) is considered conservatively to represent Holocene activity.

Along the western boundary of the landfill, three geologic cross-sections have been constructed to document the subsurface stratigraphy and possible fault-related structure beneath the site. These three sections are designated from south to north as cross-sections UKK-1-1A-1A’, 1B-1B’ and 1C-1C’ and overlap, in part, with seismic line SL-1. Similarly, two cross-sections intersect much of the northern perimeter of the landfill and are designated from west to east as cross-sections UKK-2-2A-2A’, 2B-2B’, which partly overlap with seismic line SL-2 (Plate 3). The locations of the cross-sections are shown on Plate 1, whereas Plates 2 and 3 show the geologic cross-sections UKK-1 and UKK-2, respectively. The geologic cross-sections display as many as seven primary stratigraphic horizons in the upper 30 feet (9.1 m) of material underlying the site, and coincide with the unit designations previously described in the above section. The cross-sections have a four times (4x) vertical exaggeration for the purpose of displaying thin stratigraphic and pedogenic horizons, and identifying subtle changes in stratigraphy across the site that might be representative of faulting or folding, or alternatively to original perturbations in the paleo-topography. Accompanying each exaggerated cross-section is an identical section without vertical exaggeration to better illustrate actual field conditions (shown on Plates 2 and 3). The cross-sections allow possible interpretation of as many as four (4) relatively large folds or warps, and 21 features with representative elevation changes across stratigraphic and/or pedologic boundaries. These features (labeled AA to DD; and A to U) are shown graphically in index figures 10a and 10b. The estimated amount and style of vertical separation of the features are summarized in Tables 3 and 4 and discussed below.

6.2.1 Geologic Sections Along Seismic Line SL-1

Cross-sections 1A-1A', 1B-1B' and 1C-1C' correspond with portions of seismic line SL-1. Geologic cross section 1A-1A' is oriented along the southern end of seismic reflection line SL-1 and intersects a narrow zone of previously interpreted steeply dipping faults having a normal sense of motion and coinciding with deformation zone DZ1-1 (Woolery, personal communication, 2005, see Figure 8). One broad warp (feature AA) and five possible distinct changes in the elevations of some stratigraphic contacts (features A to E) are inferred in cross section UKK-1A-1A'. Geologic cross section UKK-1B-1B' lies along the central part of seismic reflection line SL-1 and crosses a broad zone of moderately disturbed reflectors within the Metropolis Formation that are interpreted as being truncated across a near-vertical, north-dipping fault near shot point UKK-1-415 (Figure 8; Fault 2 of Blackhawk, 2003). In section UKK-1B-1B', two subtle warps (features BB and CC) and two features (features F and G) associated with possible vertical elevation changes across stratigraphic boundaries are interpreted (Tables 3 and 4). Geologic cross section UKK-1C -1C' lies along the north-central part of seismic reflection line SL-1 and intersects a steep, north-dipping fault interpreted as Fault 1 by Blackhawk (2003), and a steep, south-dipping fault interpreted by Woolery (personal communication, 2005) (Figure 8). In section UKK-1C-1C to 1C' no broad large possible structures are interpreted, however, five possible discrete features (H to J) associated with elevation changes across stratigraphic boundaries are interpreted.

6.2.1.1 Zones of Possible Broad Tilting and Warping Along Seismic Line SL-1

As shown on Plate 2, the fluvial stratigraphy within the Metropolis Formation (units 5.1 to 5.3) dips very gently southward in section UKK-1A-1A' and is somewhat suggestive of a weakly expressed monoclinal feature (Feature AA; Figure 10a and Table 3). For example, the base of unit 5.1 decreases in elevation about 5 feet (1.5 m) across the section, indicating an apparent southerly dip of about 2°. However, this prominent dip is not present in higher stratigraphic boundaries coinciding with unit 4 and the younger loess packages, suggesting that the feature, if present, formed prior to deposition of units 1 to 3. The approximate location, sense and amount of tilt of the Metropolis Formation (units 5.3 to 5.1) is consistent with deformation interpreted in line SL-1 between shot points 180 and 215 (Woolery, personal communication, 2005).

Based on north-dipping basal contacts of 5.2 and 5.1 in cross-section UKK-1B-1B' it is possible to interpret two relatively broad north-facing warps exhibiting northside-down separation. The two warps (features BB and CC) are interpreted at the southern and northern ends of the geologic profile (Figure 10a). A possible north-facing warp, feature BB, interpreted along the southern part of the section lies between DPT cores UKK-1-350 and 380 (Figure 10a). Feature BB is defined by gentle (3°), north dipping stratigraphy associated with units 5.2 and 5.1. The amount of vertical elevation change associated with the tilting is as much as about 3 feet (0.9 m) across the unit 5.2 basal contact. Unit 4 and the overlying late Pleistocene loess (units 1 to 3) packages exhibit an overall gentle north-dip to flat-lying character that is consistent with overlying topography. Feature CC is defined by a gently north dipping panel of Metropolis Formation stratigraphy (units 5.2, 5.1 and 4) located between DPT cores UKK-1-405 and 430 (Figure 10a). These units dip up to about 3° to the south and account for a decrease in elevation of about 2.25 feet (0.69 m). The overlying strata comprising the late Pleistocene loess material generally dip gently north or are nearly flat-lying.

6.2.1.2 Distinct Elevation Changes in Stratigraphy Along Seismic Line SL-1

Based on the geologic cross-sections constructed from DPT data it is permissible to interpret as many as 10 features (features A through J) aligned with moderate to abrupt vertical changes in elevations across stratigraphic boundaries (Figure 10a). Of the ten (10) possible features, seven (7) are constrained to stratigraphic horizons equal to or older than unit 4 (53.6 to 75.5 ka). It is possible to interpret as many as three features (features G, I and J) projecting into the Roxana Silt (unit 3) and Peoria Loess (units 1 and 2). Each of the ten (10) features possibly associated with fault-related deformation are discussed below.

Feature A is a low-angle, south-dipping feature that can be inferred to intersect DPT cores UKK-1-200 to 220 and exhibits a southside-down, normal sense of vertical separation. Given the range in uncertainty of the basal contact of unit 5.1, there is a relatively abrupt difference in this contact's elevation between DPT boreholes 205 and 210 (Figure 10a). Similarly, the base of unit 4 shows a trough between DPT cores 210 and 220 and a south-facing slope between DPT 215A and 220. Changes in elevation are as much as 2 feet (0.61 m) across the unit 5.1 basal contact and decrease upsection to about 1.75 feet (0.53 m) across the base of unit 4. If these features are related to fault deformation, the fault would dip gently (20° to 30°) to the south. However, an absence of a similar south-facing dip panel across the basal contact of unit 3 (within a resolution of ~0.4 feet [~0.12 m]) indicates an absence of deformation of the Roxana Silt (Figure 10a and Plate 2).

Distinct vertical changes in elevation across stratigraphic boundaries associated with basal units 5.2 and 5.1 contacts between DPT cores UKK-1-205 and 215A defines the location of feature B (Figure 10a). Feature B dips north about 40° and exhibits as much as about 2 feet (0.61 m) of northside-up vertical separation across the base of unit 5.1, consistent with a reverse sense of separation. This feature does not extend upsection into the overlying nearly flat-lying stratigraphy of unit 4 (unnamed intermediate loess) within a limit of resolution of ~0.3 feet (0.09 m).

Feature C coincides with an abrupt northerly dip of the stratigraphic basal horizon of unit 5.2 that lies between DPT cores UKK-1-215A and 220 (Figure 10a). This feature is relatively steep (80° to 90°) and exhibits a north-side down vertical separation of as much as ~1.75 feet (0.53 m) across the base of unit 5.2, consistent with a normal sense of separation. Feature C does not project upsection across the overlying stratigraphic boundary of unit 5.1 within a resolution of ~0.5 feet (0.15 m).

Feature D is interpreted as a near-vertical (80° to 90°) feature that separates the south-dipping (~3°) stratigraphic basal contacts of units 5.2 and 5.1 between DPT cores UKK-1-220 and 225 (Figure 10a). The southside-down vertical separation is subtle and can be interpreted to be as much as ~1.25 feet (0.38 m). This feature does not extend upward into unit 4 which dips north, or the overlying, relatively flat-lying loess deposits (units 1 to 3) within a resolution of about 0.3 feet (0.09 m).

Feature E is a near-vertical feature that is defined by a relatively abrupt change in elevation of the south-dipping (~6°) basal contact of unit 5.2 between DPT cores UKK-1-230 and 235 (Figure 10a). The sense of separation is as much as ~1.75 feet (0.53 m) with a southside-down sense of separation. Feature E cannot be projected upsection through the relatively flat-lying stratigraphic boundaries of the upper Metropolis Formation (unit 5.1) and loess deposits (units 1 to 4) within a resolution ~0.3 feet (0.09 m).

Feature F is interpreted as dipping south about 35° and coincides with the broad north-directed tilting (~5°) associated with feature BB near DPT cores UKK-1-350 to 380 (Figure 10a). Feature F vertically separates the basal contacts associated with units 5.2, 5.1, and 4.0 with the apparent separation being reverse and progressively decreasing upsection. The apparent vertical separation is as much as about 3 feet (0.91 m) across the base of unit 5.2 and decreases upsection to about 1 foot (0.30 m) across the basal contact of unit 4. Within a resolution of about 0.4 feet (0.12 m), the overlying loess packages are generally flat-lying to gently north-dipping above this zone and show no evidence of vertical separation. Feature F closely aligns with Blackhawk (2003) Fault 2, but exhibits a reverse sense of separation in contrast to the normal separation interpreted across Fault 2.

Feature G coincides with abrupt north-dipping (~10°) fluvial stratigraphy of the Metropolis Formation and units 5.2 and 5.1 between DPT cores UKK-1-405 to 415 (Figure 10a). The feature aligns with the broad north-facing warp of feature CC, as well as a near-vertical fault interpreted in line SL-1 (deformation zone DZ1-2 of Woolery; Figure 8). Feature G dips approximately 45° to the south, and exhibits a northside-down elevation change that is consistent with reverse separation. Across the basal contact of unit 5.2 there is as much as about 1.75 feet (0.53 m) of vertical separation. The overlying Peoria Loess (units 1 and 2) does not appear vertically offset within a limit of resolution of about 0.4 feet (0.12 m).

Feature H coincides with the interpretation of a shallow (20°) south-dipping feature that coincides with an abrupt inflection (~7°) of the lowermost units (basal contact of unit 5.2) of the Metropolis Formation, and can be projected upsection across the basal contacts associated with units 5.1 and 4.0 between DPT cores UKK-1-530 and 555 (Figure 10a). The feature exhibits a southside-up vertical separation ranging from about 2 feet (0.61 m) across the unit 5.2 contact and decreasing upsection to about 1.25 feet (0.38 m) across the basal contact of unit 4. The sense of separation is consistent with reverse motion along feature H. The overlying loess packages of units 1 to 3 generally are flat-lying within a limit of resolution of ~0.4 feet (0.12 m). Lastly, feature H closely aligns with Blackhawk (2003) Fault 1, however it displays an opposite sense of vertical separation to that of Fault 1.

Feature I lies between DPT cores UKK-1-565 and 575 and coincides with the alignment of a discrete change in elevation across the south-dipping (~12°) basal boundaries of units 5.2 and 5.1 (Figure 10a). The feature dips south approximately 70°, and exhibits a sense of separation that is consistent with a southside-down, normal separation. The estimated change in elevation across feature I is about 3.25 feet (1.0 m) at the basal contact of unit 5.2, and decreases upsection to about 1.25 feet (0.4 m) across the base of unit 5.1. It is possible to interpret as much as 2 feet (0.61 m) of vertical separation within the overlying loess units, however, because several of the inferred separations are based on anomalous contacts in DPT core UKK-1-575, these displacements are considered suspect. Furthermore, the upward projection of feature I from the Metropolis Formation into the overlying loess boundaries is highly questionable, because these cores experienced adverse drilling and sampling conditions imparted by moderately thick artificial fill that may have influenced the location of the stratigraphic boundaries. Lastly, the overall sense of separation is consistent with Woolery's (personal communication, 2005) re-interpretation of seismic line SL-1, however, the apparent vertical separations that are possible across the loess boundaries are considered unlikely.

Feature J is interpreted as a near-vertical alignment of elevation changes across the north-dipping (~6°) base of units 5.2 and 5.1 horizons between DPT cores UKK-1-585 and 590 along the northern end of section UKK-1-C-C' (Figure 10a). The feature is defined primarily by abrupt north-dipping stratigraphic panels of the Metropolis Formation that exhibit a northside-down sense of vertical separation. It is permissible to project feature J upsection into the two lowermost loess packages (units 3 and 2); however, the amount of vertical separation in the overlying loess unit is inconsistent stratigraphically, and suggests that the presence of artificial fill influences the elevation at which the stratigraphic contacts are encountered. Feature J does not align with any previously interpreted faults of seismic line SL-1.

6.2.2 Geologic Cross Sections Along Seismic Line SL-2

Geologic cross-sections UKK-2A-2A' and 2B-2B' coincide with seismic line SL-2, and lie along the northern perimeter of the present-day landfill (Plates 1 and 3). Geologic section UKK-2A-2A' overlaps with a narrow zone of previously interpreted steeply dipping reverse faults, including Fault 1 of Blackhawk (2003), and numerous discontinuities of Woolery (zone DZ2-1; personal communication, 2005) (Figure 9). In section UKK-2A-2A' it is possible to interpret an antiform (feature DD) and numerous distinct elevation changes (features K to P) across stratigraphic boundaries in the Metropolis Formation. Geologic cross-section UKK-2B-2B' lies along the eastern end of seismic reflection line SL-2 and spans a zone of east- and west-dipping faults interpreted by Woolery (zone DZ2-2; personal communication, 2005), as well as Fault 2 of Blackhawk (2003) (Figure 9). Overall, cross-section UKK-2B-2B' depicts: (1) relatively flat-lying stratigraphy with no prominent large structural-like features, and (2) five distinct elevation changes (features Q to U) that are limited primarily to unit 4 and older units, except for feature U that extends into Roxana Silt.

6.2.2.1 Zones of Possible Broad Tilting and Warping Along Seismic Line SL-2

It is permissible to interpret an antiform (feature DD) based on east and west tilted fluvial stratigraphy of the Metropolis Formation that span DPT cores UKK-2-319 and UKK-2-379 (Figure 10b). For example, the base of unit 5.2 dips about 6° to the east and west, and changes about 5 feet (1.5 m) in elevation across the antiform. The apparent tilting decreases upsection and is constrained primarily within units comprising the Metropolis Formation and possibly unit 4.0 (unnamed intermediate loess). Feature DD does not propagate into the overlying, gently west-dipping to nearly flat-lying loess packages of units 1 to 3 (Roxana Silt and Peoria Loess). The approximate location and sense of vertical separation, and pattern of tilted stratigraphy is consistent with deformation interpreted in line SL-2 between shot points UKK-2-310 and 360 (Figures 9 and 10b).

6.2.2.2 Distinct Elevation Changes in Stratigraphy Along Seismic Line SL-2

Based on the geologic cross-sections constructed from DPT data, it is permissible to interpret as many as 11 features (features K through U) aligned with moderate to abrupt vertical changes in elevation across stratigraphic boundaries (Figure 10b). Of the eleven (11) possible features nine (9) are constrained to stratigraphic horizons of unit 4 (53.6 to 75.5 ka unnamed intermediate loess) and older deposits. Two features (L and U) may intersect the basal boundaries of the Roxana Silt and Peoria Loess. Each of the eleven (11) features possibly associated with fault-related deformation are discussed below.

Feature K is a steeply dipping feature that coincides with a subtle westward-directed tilt (~9°) of the base of unit 5.1 (Figure 10b). It is unclear if it vertically separates the base of unit 5.2, because where the feature would project down-section and intersect unit 5.2, the basal contact lies beneath the depth of exploration. This feature exhibits a westside-down, normal component of vertical separation that accounts for 1.0 to 1.5 feet (0.3 to 0.46 m) of elevation change across the base of unit 5.1. Feature K does not extend across the base of unit 3.0 within a resolution of about 0.4 feet (0.12 m). Feature K also closely coincides with an east-dipping fault displaying normal displacement of Woolery (personal communication, 2005) but does not overlap with any faults interpreted by Blackhawk (2003).

Feature L coincides with a moderately expressed inflection of units 5.2 to 4.0 that comprise the western limb of a possible antiform (Feature DD) (Feature 10b). Feature L accounts for vertical changes in contact elevations between DPT cores UKK-2-329 to 349. The feature dips about 40° east, and vertically separates west-dipping (~10°) stratigraphy associated with basal contacts of units 5.2 and 4.0 as much as 2.0 and ~1.75 feet (0.61 and 0.53 m), respectively. It is permissible to interpret feature L as intersecting the base of unit 2.0 (Lower Peoria Loess) possibly as much as 1.0 feet, (0.3 m), however unit 1.0 (Upper Peoria Loess) is flat-lying within a resolution of about 0.6 feet (0.18 m). The character of the feature changes upsection near the base of unit 4, where it coincides with an anomalous trough rather than a continuous panel of west dipping stratigraphy. This suggests that it is unlikely feature L projects upward into the overlying Roxana Silt and Peoria Loess.

Feature M coincides with an abrupt west-tilted (10°) basal horizon of unit 5.2 within the Metropolis Formation that projects upsection across the base of a slightly less tilted (<5°) unit 5.1 (Figure 10b). These west-tilted fluvial strata define a near vertical feature consistent with a normal component of separation. Changes in elevation are up to about 2.0 and 1.5 feet (0.61 and 0.46 m) for the base of unit 5.2 and 5.1, respectively. Feature M does not offset the base of unit 4.0, or the upper loess packages, within a resolution of about 0.3 feet (0.09 m). Feature M is closely aligned with a steep west-dipping normal fault interpreted as the main fault in DZ2-1 (E. Woolery, personal communication, 2005) and as Fault 1 (Blackhawk, 2003) (Figure 9).

Feature N dips about 85° east, and coincides with east-dipping (~5°) basal contacts of units 5.2 and 5.1 (Figure 10b). The unit boundaries exhibit as much as ~1.5 feet (0.46 m) of elevation change across the feature, consistent with a down-to-the-east, normal sense of vertical separation. Feature N does not offset the base of unit 4.0, nor the overlying loess packages within a resolution of ~0.3 feet (0.09 m). This possible fault-related feature lies within the fault zone of Fault 1 (Blackhawk, 2003) and DZ2-1 (E. Woolery, personal communication, 2005) but exhibits an opposite sense of vertical separation (Figure 9).

Feature O dips east about 40° and coincides with the west-tilted (~10°) basal boundary of units 5.2, 5.1, and 4.0 (Figure 10b). The basal unit horizons of the Metropolis Formation exhibit down-to-the-west vertical separation that is consistent with a reverse sense of motion. Changes in elevation are as much as ~1.0 foot (0.30 m) across units 5.2, 5.1, and 4.0. The feature is constrained to an anomalous trough present at the base of units 5.2 and 5.1 between cores DPT 354 to 364. Feature O cannot be traced upsection into the overlying loess packages within a resolution of 1.9 feet (0.58 m) (units 3 and 2) and 0.6 feet (0.18 m) for the Upper Peoria Loess (unit 1).

Feature P is near-vertical and coincides with the west-dipping (~10°) stratigraphic boundaries of units 5.2, 5.1, and 4.0 between DPT cores 359 and 369 (Figure 10b). Feature P exhibits normal separation with the westside-down and coincides closely with Blackhawk (2003) Fault 1. Changes in elevation are as much as ~2.0 feet (0.61 m) across the base of units 5.2 and 5.1, and decrease upsection to about 0.5 to 1.0 foot (0.15 to 0.3 m) across unit 4.0. Feature P cannot be traced upsection into the younger loess packages of units 3 to 1 (Roxana Silt and Peoria Loess) within a limit of resolution of ~0.4 feet (0.12 m).

Feature Q is near-vertical, and exhibits an elevation change across the basal boundaries of units 5.2, 5.1, and 4.0 between DPT cores UKK-2-519 to 524 (Figure 10b). The vertical separation is as much as 2.0 feet (0.61 m) across the basal of units 5.2 and 5.1, and decreases upsection to about 1.5 feet (0.46 m) at the intersection with unit 4.0. The basis for the presence of this feature is driven strongly by the large (2 feet or 0.61 m) uncertainties associated with the base of units 5.2 and 5.1 observed in DPT core 519; however, this feature does not vertically separate the flat-lying unit 3 (Roxana Silt) within a resolution of about 0.4 feet (0.12 m). Feature Q lies in a region where no faults have been previously interpreted along line SL-2.

Feature R is vertical and coincides with a subtle elevation change across the base of unit 5.2 between DPT cores UKK-2-549 and 554 (Figure 10b). The vertical separation of Feature R is extensional, as much as 1.0 feet (0.30 m), and is expressed as the east-dipping (<5°) basal contact of unit 5.2. This feature does not warp any overlying stratigraphic unit boundaries within a limit of resolution of about 0.5 feet (0.15 m) (unit 5.1). The feature coincides with an east-dipping reverse fault interpreted by Woolery (personal communication, 2005) between shot points UKK-2-539 and 549 (Figure 9).

Feature S dips about 65° west and is defined by an westside-down elevation change across the west-dipping (~2°) base of units 5.2, 5.1, and 4.0 (Figure 10b). The amount of apparent normal separation across the stratigraphic boundaries is as much as 1.0 feet (0.30 m) (unit 4.0), 1.5 feet (0.46 m) (unit 5.1), and 1.0 feet (0.30 m) (unit 5.2). Feature S does not coincide with any faults interpreted in line SL-2 and does not project into overlying loess packages (Roxana Silt and Peoria Loess) within a resolution of about 0.4 feet (0.12 m).

Feature T dips about 37° west and coincides with possible gently east-dipping (~3°) stratigraphic horizons associated with units 5.2, 5.1, and 4.0 between DPT cores UKK-2-649 and 669 (Plate 10b). This west-dipping feature exhibits a reverse sense of separation that is as much as 2.0 feet (0.61 m) for the base of units 5.1 and 4.0, but considerably less across the deeper basal contact of unit 5.2. The less pronounced nature of the feature across the base of unit 5.2 and 4.0 suggests that this feature may represent the natural variability and undulations of the fluvial stratigraphy within the Metropolis Formation. Feature T does not coincide with faults previously interpreted by Woolery (personal communication, 2005), or Fault 2 of Blackhawk (2003). Lastly, feature T does not project into overlying loess packages (Roxana Silt and Peoria Loess) within a resolution of about 0.4 feet (0.12 m).

Feature U dips about 25° east and coincides with gently (2°) west-dipping strata associated with units 5.2 to 4.0, and possibly the base of unit 3 (Figure 10b). The changes in elevation of units across feature U are stratigraphically inconsistent along its projected length suggesting its projection upsection into the Roxana Silt and Peoria Loess is highly suspect. For example, vertical separations are as much as about 2 feet (0.61 m) across the base of unit 4.0 (unnamed intermediate loess), and as small as 1 foot (0.30 m) across the base of unit 5.2 (Metropolis Formation). The Lower Peoria Loess (unit 2) is flat-lying above this feature and does not reflect any warping within a limit of resolution of about 0.4 feet (0.12 m). The approximate location of feature U coincides with the general location of a feature interpreted by Woolery (personal communication, 2005) between shot points UKK-2-669 and 679, and exhibits a similar sense of vertical separation (Figure 9).

7.0 POTENTIAL FOR HOLOCENE FAULTING AT THE C-746-U LANDFILL EXPANSION

Available regional and local geologic and geophysical data in western Kentucky provide evidence of steeply dipping, northeast-striking faults lying within the Reelfoot rift that possibly connect with the FAFC of southern Illinois and northwestern Kentucky (Figures 3 and 4). The presence of northeast-trending contemporary microseismicity within this zone of poorly characterized faults suggests that some of the north- to northeast-trending structures may accommodate present-day regional strain, and thus may be similar to faults in the NMSZ (Figure 3). This investigation of Holocene faulting at the C-746-U landfill expansion provides subsurface information by which to assess the presence or absence of Holocene activity on previously interpreted northeast-striking faults (Faults 1 and 2 of Blackhawk, 2003), as well as multiple faults and folds interpreted from previous site-specific seismic lines (Woolery, personal communication, 2005) (Figures 8 and 9). These previously interpreted faults that would intersect the landfill lie within a diffuse band of contemporary microseismicity, and generally coincide with a southwestern projection of the Hobbs Creek and Barnes Creek fault zones in the FAFC of southern Illinois (Figure 4). The inferred faults of Blackhawk (2003) and Woolery (personal communication, 2005) were evaluated with respect to a regional tectonic model in which the near-vertical, northeast-striking faults accommodate oblique dextral strike-slip faulting, including components of extensional and contractional deformation that result in substantial vertical separation of horizontal strata.

This study assumes that if faults underlie the site, material displaced by these inferred faults record discrete brittle deformation in contrast to some localities associated with the 1811-1812 earthquakes, where evidence of past surface rupture is enigmatic along much of the NMSZ. The absence of primary surface rupture with this earthquake sequence may be partly a result of the rupture being broadly distributed through the thick semi-consolidated to unconsolidated saturated deposits in the Mississippi embayment. We suggest that there is only a remote possibility that the deposits encountered in this fault study may not record discrete Holocene fault rupture because the Quaternary section underlying the site is thin (<100 feet thick; 30 m). These relatively thin early to middle Quaternary fluvial materials overlain by late Pleistocene loess have been shown regionally to be displaced by faults in southern Illinois (Nelson et al., 1999: SAIC, 2004) and southeastern Missouri (Harrison et al., 1999; Baldwin et al., in press), indicating that the material underlying the proposed landfill expansion should record brittle deformation, if faulting has occurred in the recent geologic past. Also, the cores collected for this study provide direct evidence for the absence of slickensides, breccia and clay gauge across some of the interpreted fault zones of Blackhawk (2003) and Woolery (personal communication, 2005).

Based on the tectonic model described above and in patterns typical of surface-fault rupture behavior, the five geologic profiles that intersect the previously interpreted northeast-striking faults show that the strata younger than unit 3.0 (Roxana Silt) are undeformed beneath the site. Of the 25 features possibly associated with vertically separated or warped stratigraphic horizons, 20 features do not extend into unit 3.0 (Roxana Silt; Tables 3 and 4), which has an estimated age ranging between 32 and 51 ka at the site (Table 2). As noted in Section 6.0, of the five possible features that intersect the Roxana Silt, it is permissible to extend only three into the overlying Peoria Loess (10 to 25 ka). However, the presence of two of these features (I and J) is highly suspect because of their association with artificial fill, and the third feature (L) does not displace the overlying Upper Peoria Loess (unit 1). Collectively, the findings from this study strongly suggest that the previously interpreted faults at the landfill are not Holocene active.

Only in a few instances is it permissible to interpret fault-like features extending upward into the Roxana Silt (unit 3) and Peoria Loess (unit 2). These interpretations are highly questionable, especially when the features are evaluated with respect to the geologic sections having zero vertical exaggeration, and/or the near-surface sampling conditions (i.e., presence of artificial fill). Nowhere along the profiles do we interpret a clear or distinct separation of the Upper Peoria Loess (unit 1) or the base of the Lower Peoria Loess (unit 2) that unequivocally can be interpreted as fault-related. We argue for the absence of the upward projection of these features into the Peoria Loess when: (1) there is a high degree of uncertainty in the location of basal contacts because of compression, artificial fill, or highly-saturated loess; (2) the fault-like feature has an unrealistically low inclination; and (3) a preponderance of DPT data constrain the majority of the fault-like features to the Metropolis Formation and unnamed intermediate loess (unit 4).

Many of the possible vertical steps interpreted in the Metropolis Formation (units 5.3 to 5.1) also can be explained alternatively by non-tectonic fluvial processes (i.e., channel erosion and deposition). For instance, the base of unit 5.1 typically is abrupt, erosional, and characterized by coarse-grained fluvial deposits overlying fine-grained overbank deposits. This contact often defines the base of a prominent channel that varies in thickness and elevation through scouring and natural stratigraphic undulations. Unit 5.3 also is a gravelly, coarse-grained sand likely associated with Pleistocene braided stream deposits. These types of fluvial deposits often have a natural undulatory surface related to local channel scour, and deposition of mid-channel sand or gravel bars. When buried and viewed in profile, these contacts can appear as vertical steps. We interpret that many of these steps are a result of fluvial erosion, lateral accretion, or other fluvial processes, but we cannot absolutely preclude the possibility of fault displacement.

In short, we are unable to unequivocally preclude that some changes in horizon elevation are related to tectonic displacement. Therefore, we conservatively assume that all of the features identified in the sections are of potential tectonic origin. This is especially evident when features I, J and L are considered anomalous due to abrupt, sampling-induced variations in stratigraphic continuity, or compared against the preponderance of DPT data from the direct vicinity of the features that indicate Holocene inactivity (i.e., feature L). Under these conditions and assumptions, unit 4 is the youngest horizon potentially displaced by faulting at the site. Unit 4, an unnamed intermediate loess, is dated at about 53.6 to 75.5 ka, and thus pre-dates the Holocene by several tens of thousands of years. The study findings suggest that the previously interpreted faults of Blackhawk (2003) and Woolery (personal communication, 2005) were active during the late Pleistocene but not during the Holocene, and have vertical displacements typically ranging from about 1 to 3 feet (0.3 to 0.9 m). This late Pleistocene age of possible faulting at the C-746-U landfill expansion more closely correlates with the age of faulting associated with structures comprising the FAFC of southern Illinois (Nelson et al., 1999). Therefore, this fault-rupture hazard investigation indicates that: (1) there is a strong likelihood of no Holocene faulting across the existing and proposed landfill expansion; and (2) the C-746-U landfill is not subject to fault-setback conditions outlined in CFR, Subtitle D, Title 40. A summary of the findings of the DPT-based geologic profiles is provided below.

7.1 Fault 1 and Deformation Zone DZ2-1

Fault 1 of Blackhawk (2003) and deformation zone DZ2-1 of Woolery (personal communication, 2005) are intersected by DPT cross-sections UKK-1C-1C' and UKK-2A-2A' (see Plate 1, and Figures 8 and 9 for locations). Blackhawk (2003) interprets about 20 feet (6.1 m) of vertical displacement of either the Metropolis Formation or Mounds Gravel across this fault, and maps the fault to within 15 to 20 feet (4.6 to 6.1 m) of the ground surface. Alternatively, Woolery (personal communication, 2005) interprets a "half-flower" structure that vertically displaces the Mounds Gravel about 10 feet (3.0 m) and the Metropolis Formation about 2 feet (0.61 m) (Figure 9). In either case, many of the DPT cores would intersect the fault zones, and thus should be expressed in the lower part of the cross-sections, if present.

The DPT core data from these sections depict a possible northeast-trending, buried topographic high (antiform/feature DD) limited mostly to the Metropolis Formation, that may be reflective of tectonic deformation (e.g., folding and faulting associated with a "half-flower" structure inferred by Woolery)

(Figure 10b). The antiform has an overall southerly plunge, and vertical relief estimated to be as much as 5 feet (1.5 m) of the base of unit 5.2, whereas the overlying younger loess sheets of units 3 to 1 (Roxana Silt and Peoria Loess) are relatively horizontal above the tilted fluvial strata of the Metropolis Formation. These stratigraphic and structural relations suggest that, if the antiform (feature DD) is related to tectonic deformation, it pre-dates the Holocene (see Plate 3). Similarly, fault-like features (K, M through P) inferred from these sections are constrained primarily to the Metropolis Formation (units 5.3 to 5.1) and the unnamed intermediate loess (unit 4) suggesting that the features are pre-Holocene in age (Tables 3 and 4). The fault-like features typically exhibit about 1 to 3 feet (0.3 to 0.9 m) of vertical separation of basal contacts within the Metropolis Formation, consistent with both a normal and reverse sense of motion.

We acknowledge that it is permissible to infer near-surface faulting of the Peoria Loess across a few of the features shown in sections UKK-1C-1C' and UKK-2A-2A'; however, we consider this scenario to be unlikely. For instance, features I and J of section UKK-1C-1C' can be inferred to intersect or come close to the base of the Peoria Loess (Figure 10a). The cores used to define features I and J underwent significant compression, which resulted in uncertainty in evaluating the elevations and correlation of stratigraphic horizons within the upper 10 feet (3.0 m). In cores UKK-570 to 590, and directly below this anomalous zone of compression, it is reasonable to infer vertical separation across the basal contacts of units 5.1 and 5.2; but above the base of unit 4, features I and J suspiciously align with the southern and northern margins of a body of artificial fill (Figure 10a). If features I and J represent faults, we interpret a pre-Holocene age of faulting based on: (1) the presence of fill which artificially distorts the basal contacts of the near-surface loess due to compression; and (2) an observed increase in vertical separation upsection along the feature, indicating the amount of displacement is stratigraphically inconsistent. Similarly, we interpret that it is unlikely that feature L (section UKK-2A-2A') extends across the basal contact of unit 2 because of: (1) a moderate inclination (45°), and (2) a direct association with other adjacent fault-like features (M through P) that do not displace the Peoria Loess (Figure 10b).

In summary, the cross-sections intersecting Fault 1 and DZ2-1 depict primarily near-vertical, fault-like features coincident with zones of apparent warping or folding (Figures 10a and 10b). The fault-like features typically exhibit an apparent vertical separation consistent with both normal and reverse components of motion that extends across the basal unit 5.1 and 5.2 contacts. The youngest potentially displaced unit in these sections is the unnamed intermediate loess (unit 4), indicating that the age of Fault 1 (Blackhawk, 2003) and faults interpreted in deformation zones DZ2-1, pre-date deposition of unit 3 (Roxana Silt) at about 32 to 51 ka.

7.2 Fault 2 and Deformation Zones DZ1-2 and DZ2-2

DPT core data used in constructing sections UKK-1B-1B' and UKK-2B-2B' provide the basis for assessing the presence or absence of Fault 2 (Blackhawk, 2003) and the broad zone of deformation delineated by zones DZ1-2 and DZ2-2 (Woolery, personal communication, 2005) (Figures 8 to 10). Woolery (personal communication, 2005) interprets a "positive" flower structure deforming the Metropolis Formation along faults with as much as 2 to 3 feet (0.6 to 0.9 m) of vertical displacement. The geologic sections prepared from the DPT data and presented without vertical exaggeration exhibit nearly flat-lying stratigraphy across the entire north-central and northeastern part of the landfill (Plate 3). At an exaggerated scale (4x), these same DPT data delineate seven features with vertically separated stratigraphic boundaries. Five of the seven features (features F, T to Q) appear to intersect the Metropolis Formation and the unnamed intermediate loess (unit 4), and the remaining two features (G and U) project upward across the Roxana Silt (unit 3) basal contact (Figure 10a and 10b).

The likelihood of features G and U extending beyond unit 4 is believed to be low. Feature G dips south, would have a reverse sense of motion, and can be interpreted as intersecting the basal contact of unit 3 (Roxana Silt). However, it does not vertically separate the base of the Peoria loess (unit 2), which dips in an opposite direction of the underlying units within a resolution of about 0.4 feet (0.12 m). Profile UKK-1B-1B', without vertical exaggeration, shows that feature G is moderately well expressed across the basal unit 5.2 contact, but is barely discernable across the basal contacts of units 5.1 and 4. These relationships suggest that if feature G is present, it most likely is present only within the Metropolis Formation (Figure 10a). Similarly, it is possible that feature U of section UKK-2B-2B' projects upward into unit 3 (Roxana Silt), but because of its moderately low inclination (about 37°), and a pattern of stratigraphically inconsistent vertically separated contacts (i.e., displacement increases upsection), there is a very low likelihood that feature U has a tectonic origin.

In summary, geologic profile UKK-2B-2B' provides an extensive DPT data set that shadows much of the northern part of the landfill. This section shows laterally continuous, nearly horizontal stratigraphic contacts along its entire length. Where the profile intersects the surface projection of Fault 2 (Blackhawk, 2003) and deformation zone DZ2-2 (Woolery, personal communication, 2005), the stratigraphic information indicates that there is no distinct vertical separation across geologic strata within the Metropolis Formation. This is similarly true with DPT data interpreted in the north-south oriented profile of UKK-1B-1B' and crossing Fault 2, with the minor exception that several subtle perturbations at the base of units 5.1 and 5.2 occur along this section. Estimated amounts of potential vertical displacements across the inferred fault-like features are as much as 3 feet (0.9 m), consistent with Woolery's (personal communication, 2005) interpretation of the geophysical profiles. Collectively, the sections show: (1) the presence of undeformed, latest Pleistocene to Holocene deposits beneath the central part of the C-746-U landfill, and therefore (2) an absence of Holocene faulting beneath the landfill, and (3) the presence of some possible fault-like features aligned with previously interpreted Fault 2 (Blackhawk, 2003) and DZ2-2 (Woolery, personal communication, 2005)within units older than unit 4 (unnamed intermediate loess dated at 53.6 to 75.5 ka).

7.3 Faults along the Southwestern Perimeter of the Landfill: Deformation Zone DZ1-1

DPT data collected along section UKK-1A-1A' shadow deformation zone DZ1-1 along the southwestern perimeter of the landfill (Plates 1 and 2). Deformation zone DZ1-1 is characterized by a series of steep, north- and south-dipping faults that exhibit both normal and reverse displacement (Woolery, personal communication, 2005). The exaggerated geologic section depicts the gentle south-dipping, undulatory stratigraphic contact of unit 5.2 that projects below the depth of exploration. The overlying strata also have a gentle southerly dip, but at apparent inclinations that progressively decrease upward to the base of unit 4, which has a southerly dip that is parallel with the present-day topographic surface (Plate 1). A total of five possible fault-related features are interpreted on this cross-section, with four of the features (B to E) present only in the Metropolis Formation (units 5.3 to 5.1). Only feature A is interpreted to extend upward into unit 4. However, because this feature is inclined at less than 30°, feature A probably is not related to faulting in this tectonic environment. Within a resolution of about 0.4 feet (0.12 m), none of the five features interpreted in section UKK-1A-1A' is associated with vertical separation of the basal contact of the Lower Peoria Loess (unit 2). Therefore, cross section UKK-1A-1A' shows continuous stratigraphy the faults in deformation zone DZ1-1 interpreted by Woolery (personal communication, 2005). We interpret that these faults have not experienced Holocene fault displacement and thus are judged to be inactive.

8.0 CONCLUSIONS

This subsurface investigation using 86 DPT cores, each approximately 30 feet (9.1 m) long, provides detailed stratigraphic information for characterizing the locations and age of possible faults previously interpreted beneath the C-746-U landfill. Analysis of these cores, including detailed logging and stratigraphic correlations of more than 2,580 feet (about 790 m, or one-half mile) of core, provide the most comprehensive information to date on near-surface stratigraphy beneath the landfill. The focus of this analysis was on several possible faults previously identified on geophysical profiles, which appear to be the most likely candidates for possible Holocene activity at the site. The locations and ages of the possible faults are constrained by stratigraphic continuity of late Pleistocene loess and fluvial deposits, as well as pedogenic horizons developed in these deposits. The geologic cross-sections developed from the DPT data allow the possible interpretation of as many as four relatively "broad" folds or warps, and 21 features with elevation changes across stratigraphic and/or pedologic boundaries. The 25 potential fault-related features identified during this study represent the most distinct and vertically continuous features within the DPT geologic cross-sections that could be interpreted as faulting or folding. On the basis of the DPT data, there is no evidence that Faults 1 and 2 of Blackhawk (2003), as well as the deformation interpreted by Woolery (personal communication, 2005), have displaced latest Pleistocene to Holocene deposits. Therefore, we interpret that these faults have been inactive during the Holocene (past 11,000 years) and probably during the past 15,000 years. Additional possible deformation-related features could be interpreted elsewhere from the DPT data, but these likely would be present only within units 5.2 and 5.1, and thus would represent pre-Holocene displacement. Therefore, based on the collection, documentation, and analysis of the 86 detailed DPT cores within the C-746-U landfill area, we conclude:

- Previously acquired and interpreted geophysical data from the vicinity of the PGDP collectively indicate this part of western Kentucky is intersected by predominantly moderate to steeply dipping, north-to northeast-striking late Quaternary faults that exhibit normal and reverse displacement. Structural models of the region hypothesize that these faults also have accommodated oblique dextral displacement during the late Quaternary, however, no master strike-slip fault has been identified along which the majority of this hypothesized strain was accommodated.

- Collectively, there are at least seven late Pleistocene distinct stratigraphic and pedogenic horizons present in the upper 30 feet (9.1 m) of geologic material at the C-746-U landfill. The upper three units (i.e., the Upper Peoria Loess, the Lower Peoria Loess, and the Roxana Silt) generally are flat-lying and mantle pre-existing topography. In contrast, the four lower horizons have rare subtle to abrupt undulations in stratigraphic contacts, which may reflect fluvial depositional processes and/or tectonic deformation.

- Numerical dating of several late Quaternary strata using Optically Stimulated Luminescence (OSL) methods provides well constrained ages on eolian and fluvial deposits beneath the site, including an unnamed loess (53.6 to 75.5 ka), the Roxana Silt (32 to 50 ka), the Lower Peoria Loess (22 to 30 ka) and the Upper Peoria Loess (10 to 25 ka).

- The closely-spaced DPT data provide evidence for the continuity of undeformed late Pliestocene strata (Upper Peoria Loess) beneath the C-746-U landfill, and thus for no Holocene displacement along previously interpreted faults beneath the C-746-U landfill.

- The most recent fault displacement, if present at the site, is constrained to post-date deposition of unit 4, an unnamed loess deposit between the 53.6 and 75.5 ka based on OSL dating at the site.

- The late Pleistocene age of inferred faulting at the site is similar to the youngest age of faulting reported by Nelson et al. (1999) along FAFC northeast-striking faults in southern Illinois.

- This subsurface exploration does not span all zones of deformation interpreted in seismic reflection lines SL-1 and SL-2; however, the DPT core data span the most prominent zones of deformation interpreted by Blackhawk (2003) and Woolery (personal communication, 2005), and thus, collectively suggest that the northeast-striking faults in the direct vicinity of the landfill have not experienced Holocene displacement.

- The interpretation of the DPT data strongly suggests the absence of a surface-fault rupture hazard at the landfill that could significantly impact the design of the proposed and existing facilities.

- On the basis of the findings of this study, and in compliance with 2005 Code of Federal Regulations, Subtitle D, Title 40, Part 258, subpart B (258.13), a setback of 200 feet (60.1 m) from the previously interpreted faults of Blackhawk (2003) and Woolery (personal communication, 2005) is unwarranted.

9.0 REFERENCES

Amos, D.H., and Finch, W.I., 1968, Geologic map of the Calvert City quadrangle, Kentucky-Illinois, Kentucky Geological Survey, Map GQ-731.

Amos, D.H., and Wolfe, E.W., 1966, Geologic map of the Little Cypress quadrangle, Kentucky-Illinois, Kentucky Geological Survey, Map GQ-554.

Autin, W.J., Burns, S.F., Miller, B.J., Saucier, R.T., and Snead, J.L., 1991, Quaternary geology of the Lower Mississippi River Valley, *in* Morrison, R.B., ed., Quaternary nonglacial geology; Conterminous U.S.: Geological Society of America, The Geology of North America, Boulder, Colorado, v. K-2, p. 547-582.

Baldwin, J.N., Witter, R.C., Vaughn, J.D., Harris, J.B., Sexton, J.L., Lake, M.A., Forman, S.L., and Barron, A.D., *in press*, Geological characterization of the Idalia Hill fault zone and its structural association with the Commerce geophysical lineament, Idalia, Missouri: *submitted to* the Bulletin of the Seismological Society of America.

Bechtel Jacobs Company, LLC, 2003, Technical memorandum for the C-746-U landfill fault study at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky, unpublished consultant report dated October, 2003.

Bettis III, E.A., Muhs, D.R., Roberts, H.M., and Wintle A.G., 2003, Last glacial loess in the conterminous USA: Quaternary Science Review, 22, p. 1907-1946.

Birkeland, P.W., 1986, Soils and Geomorphology, Oxford University Press, 372 p.

Blackhawk Geoservices, 2003, Final shear wave seismic survey report, C-746-U landfill seismic assessment, Paducah Gaseous Diffusion Plant, Paducah, Kentucky, unpublished consultant reported dated October, 2003.

Blum, M.D. Guccione, M.J., Wysocki, D.A., Dobret, P.C., and Rutledge, E.M., 2000, Late Pleistocene evolution of the lower Mississippi River Valley, southern Missouri to Arkansas: Geological Society of America Bulletin, v. 112, no. 2, p. 221-235.

Braile, L.W., Keller, G.R., Hinze, W.J., Lidiak, E.G., 1982, An ancient rift complex and its relation to contemporary seismicity in the New Madrid Seismic zone: Tectonics, 1, p. 225-237.

Curry B.B., and L.R. Follmer, 1992, The last interglacial-glacial transition in Illinois, Geological Society of America Special Paper 270, p. 71-88.

Drahovzal, J.A. and Hendricks, T.D., 1996, Geologic features relevant to ground-water flow in the vicinity of the Paducah Gaseous Diffusion Plant, unpublished Final Report submitted to Federal Facilities Oversight Unit: Environmental Remediation for the Paducah Gaseous Diffusion Plant, by Kentucky Geological Survey, University of Kentucky.

Ervin, C.P., and McGinnis, L.D., 1975, Reelfoot rift-reactivated precursor to the Mississippi Embayment: Geological Society of America Bulletin, v. 86, p. 1287-1295.

Esling, S. P., Hughes, W.B., and Graham, R.C., 1989, Analysis of the Cache Valley deposits in Illinois and implications regarding the late Pleistocene-Holocene development of the Ohio River: Geology, v. 17, p. 434-437.

Finch, W. 1967, Geologic map of the part of the Joppa Quadrangle, McCracken County, Kentucky: U.S. Geological Survey Map GQ-652, scale-1:24,000.

Fisk, H.N., 1944, Geological investigation of the alluvial valley of the lower Mississippi River; Vicksburg, Mississippi River Commission, War Department, U.S. Corps of Engineers, p. 39-40.

Follmer, L.R., 1983, Sangamon Geosol and Wisconsinan pedogenesis in the Midwestern United States, *in* Porter, S.C., ed., Late Quaternary Environments of the United States, v. 1, The Pleistocene, University of Minnesota Press, Minneapolis, p. 138-144.

Follmer, L.R., 1984, Soil – An Uncertain Medium for Waste Disposal. Proceedings of the 7th Annual Madison Waste Conference, 1984, Madison, Wisconsin, pp. 296-311.

Follmer, L.R., 1996. Loess studies in central United States: Evolution of Concepts:,Engineering Geology, 45 Fisk Symposium Volume, p. 287-304.

Forman S.L. and Pierson, J., 2002, Late Pleistocene luminescence chronology of loess deposition in the Missouri and Mississippi river valleys, United States: Paleogeography, Palaeoclimatology, Palaeoecology 186, p. 25-46.

Frye, J.C., Glass, H.D., and Willman, H.B., 1962, Stratigraphy and mineralogy of the Wisconsinan loesses in Illinois: Illinois State Geological Survey Circular 334, 55 p.

Grimley, D.A., Follmer, L.R., Hughes, R.E., and Solheid, P.A., 2003, Modern, Sangamon, and Yarmouth soil development in loess of unglaciated southwestern Illinois: Quaternary Science Reviews, v. 22, p. 225-244.

Hansel, A.K., and Johnson, W.H., 1996, Wedron and Mason Groups: Lithostratigraphic reclassification of deposits of the Wisconsin Episode, Lake Michigan Lobe Area: Illinois State Geological Survey Bulletin 104, 116 p.

Harrison, R.W., Hoffman, D., Vaughn, J.D., Palmer, J.R., Wiscombe, C.L., McGeehin, Stephenson, W.J., Odum, J.K., Williams, R.A., and Forman, S.L., 1999, An example of neotectonism in a continental interior-Thebes Gap, Midcontinent, United States.

Hildenbrand, T.G., Kane, M.F., and Hendricks, J.D., 1982, Magnetic basement in the upper Mississippi embayment region - A preliminary report, *in* F. A. McKeown and L. C. Pakiser, eds., Investigations of the New Madrid, Missouri, earthquake region, U.S. Geological Survey Professional Paper 1236, p. 39-53.

Hildenbrand, T.G., and Ravat, D., 1997, Geophysical setting of the Wabash Valley fault system: Seismological Research Letters, v. 68, no. 4, p. 567-585.

Jain, M., Murray, A.S., Bøtter-Jensen, L., 2003, Characterisation of blue-light stimulated luminescence components in difference quartz samples: implications for dose measurement: Radiation Measurements, 37, p. 441-449.

Jenny, H., 1941, Factors of soil formation, McGraw-Hill, New York, 721 p.

Johnston, A.C., and Schweig, E.S., 1996, The enigma of the New Madrid Earthquakes of 1811-1812: Annual Reviews of Earth and Planetary Science, v. 24, p. 339-384.

Kane, M.F., Hildenbrand, T.G., and Hendricks, J.D., 1981, Model for the tectonic evolution of the Mississippi embayment and its contemporary seismicity: Geology, v. 9, p. 563-568.

Kolata, D.R., and Nelson, W.J., 1991, Tectonic history of the Illinois Basin, *in* Leighton, M.W., Kolata, D.R., Oltz, D.F., and Eidel, J.J., eds., Interior Cratonic Basins, American Association of Petroleum Geologists Memoir 51, p. 263-285.

Kolata, D.R., and Hildenbrand, T.G., 1997, Structural underpinnings and Neotectonics of the southern Illinois Basin: An overview: Seismological Research Letters, v. 68, no. 4, p. 499-510.

Langston, C. and Street, R., 1998, Acquisition of SH-wave seismic reflection and refraction data in the area of the northeastward trending contaminant plume at the PGDP, unpublished Final Report prepared by Langston and Street of the Department of Geological Sciences, University of Kentucky, Lexington, Kentucky.

Leigh, D.S., 1994, Roxana silt of the Upper Mississippi Valley: Lithology, source and paleoenvironment. Geological Society of America Bulletin 106, pages 430-442.

Leigh, D.S. and Knox, J.C., 1993, AMS radiocarbon age of the upper Mississippi Valley Roxana Silt: Quaternary Research 39, no. 3, p. 282-289.

McBride, J.H., Sargent, M.L., and Potter, C.J., 1997, Investigating possible earthquake-related structure beneath the southern Illinois Basin from seismic reflection: Seismological Research Letters 68, no. 4, p. 641-649.

McBride, J.H., Nelson, W.J., and Stephenson, W.J., 2002, Integrated geological and geophysical study of Neogene and Quaternary-age deformation in the northern Mississippi embayment: Seismological Research Letters v. 73, no. 5, p. 597-627.

Nelson, W.J., 1991, Structural styles of the Illinois Basin, *in* Leighton, M.W., Kolata, D.R., Oltz, D.F., and Eidel, J.J., eds., Interior Cratonic Basins, American Association of Petroleum Geologists Memoir 51, p. 209-243.

Nelson, W.J., Denny, F.B., Devera, J.A., Follmer, L.R., and Masters, J.M., 1997, Tertiary and Quaternary tectonic faulting in southernmost Illinois: Engineering Geology, 46, p. 235-258.

Nelson, W.J., Denny, F.B., Follmer, L.R., and Masters, J.M., 1999, Quaternary grabens in southernmost Illinois: Deformation near an active intraplate seismic zone: Tectonophysics 305, p. 381-397.

Nelson, J.W., Masters, J.M., and Follmer, L.R., 2002, Surficial geology, Metropolis Quadrangles, Massac County, Illinois, scale: Illinois Geological Survey, Illinois geologic quadrangle map, IGQ-Metropolis-SG, 1:24,000, two sheets.

Olive, W.W., 1966, Lake Paducah of late Pleistocene age, in western Kentucky and southern Illinois: U.S. Geological Survey Professional Paper 550-D, p. D87-D88.

Olive, W.W., 1966, Geologic map of the Paducah East quadrangle in western Kentucky, Kentucky Geological Survey, Map GQ-531.

Olive, W.W., 1980, Geologic maps of the Jackson Purchase Region, Kentucky: U.S. Geological Survey Map I-1217, 1 sheet, 11 p.

Phillips, 1992, taken from Science Applications International Corporation, 2004, Seismic investigation report for siting of a potential on-site CERCLA waste disposal facility at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky, unpublished consultant report, dated March 2004, by SAIC for U.S. Department of Energy.

Potter, C.J., Goldhaber, M.B., Heigold, P.C., and Drahovzal, J.A., 1995, Structure of the Reelfoot-Rough Creek rift system, Fluorspar Area Fault Complex, and Hicks Dome, southern Illinois and western Kentucky-new constraints from regional seismic reflection data: U.S. Geological Survey Professional Paper 1538-Q, 19 pp., 1 plate.

Potter, C.J., Drahovzal, J.A., Sargent, M.L., and McBride, J.H., 1997, Proterozoic structure, Cambrian rifting, and younger faulting as revealed by a regional seismic reflection network in the southern Illinois Basin: Seismological Research Letters, v. 68, no. 4, p. 537-552.

Pryor, W.A., and Ross, C.A., 1962, Geology of the Illinois parts of the Cairo, La Center and Thebes quadrangles; Illinois State Geological Survey Circular 332, 39 p.

Rhea, S., Wheeler, R.L., and Tarr, A.C., 1995, Map showing seismicity and sandblows in the vicinity of New Madrid, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map-2264-A, 1:250,000.

Science Applications International Corporation, 1994, Solid waste landfill subsurface investigation report, unpublished consultant report prepared for U.S. Department of Energy, under contract 18B-99069C.

Science Applications International Corporation, 2004, Seismic investigation report for siting of a potential on-site CERCLA waste disposal facility at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky, unpublished consultant report dated March 2004, by SAIC for U.S. Department of Energy.

Saucier, R.T., 1996, Geomorphology and Quaternary geologic history of the lower Mississippi Valley: Army Engineering Waterways Experiment, v. 1 and 2, Vicksburg Mississippi, U.S. Department of Commerce.

Sexton, J.L., Henson, H., Koffi, N.R., Coulibaby, M., and Nelson, W., 1996, Seismic reflection and georadar investigation of the Barnes Creek area in southeastern Illinois [abs.]: Seismological Society of America, Annual Meeting, St. Louis, April 3, 1996.

Stearns, R.G., 1957, Cretaceous, Paleocene, and Lower Eocene geologic history of the northern Mississippi embayment: Geological Society of America Bulletin, v. 68, p. 1077-1100.

Stearns, R.G., and Marcher, M.V, 1962, Late Cretaceous and subsequent structural development of the northern Mississippi embayment area: Geological Society of America Bulletin, v. 73, p. 1387-1394.

Trumbore, S.E., 1998, Radiocarbon geochronology, *in* J.M. Sowers, J.S. Noller and W.R. Lettis, (eds.), Dating and Earthquakes: Review of Quaternary Geochronology and Its Application to Paleoseismology, U.S. Nuclear Regulatory Commission, NUREG/CR-5562, p. 2-69 to 2-100.

U.S. Army Corps of Engineers, 2000, Archival photo analysis Paducah Gaseous Diffusion Plant, unpublished government report dated September 2000.

U.S. Department of Agriculture, 1976, Soil survey of Ballard and McCraken Counties, Kentucky, Soil Conservation Service in cooperation with the Kentucky Agricultural Experiment Station.

Wayne, W.J., and Zumberge, J.H., 1965, Pleistocene geology of Indiana and Michigan, *in* Wright, H.E., and Frey, D.G., eds, The Quaternary of the United States: International Association of Quaternary Research, p. 63-68.

Wheeler, R.L., 1997, Boundary Separating the seismically active Reelfoot Rift from the sparsely seismic Rough Creek Graben, Kentucky and Illinois: Seismological Research Letters, v. 68, no. 4, p. 586-598.

Wheeler, R.L., 2005, Known or suggested Quaternary tectonic faulting, Central and Eastern United States-New and updated assessments for 2005, U.S. Geological Survey Open-File Report 1336, 37 p.

Woolery, E.W., and Street, R., 2002, Quaternary fault reactivation in the Fluorspar Area Fault Complex of Western Kentucky: Evidence from shallow SH-wave reflection profiles: Seismological Research Letters, v. 73, no. 5, p. 628-639.

Table 2. OSL Laboratory Results: C-746-U Landfill Expansion, Paducah, Kentucky

Core Designation	Section Line	Depth (Feet)	Lab Number	Sample Material	OSL Age (ka)[4]	Unit
UKK-1-215	UKK-1A-1A'	5.8 – 6.0	UIC 1693IR[1]	Silt/Loess	16.6 ± 1.2	Upper Peoria Loess (unit 1)
UKK-1-415	UKK-1B-1B'	5.6 – 5.9	UIC 1698IR	Silt/Loess	19.3 ± 1.4	Upper Peoria Loess (unit 1)
UKK-2-344	UKK-2A-2A'	4.5 – 4.7	UIC 1695IR	Silt/Loess	23.5 ± 1.7	Upper Peoria Loess (unit 1)
UKK-2-344	UKK-2A-2A'	4.5 – 4.7	UIC 1695IRr[2] (Duplicate)	Silt/Loess	22.3 ± 1.6	Upper Peoria Loess (unit 1)
UKK-2-344	UKK-2A-2A'	4.5 – 4.7	UIC 1695IG[3] (Duplicate)	Silt/Loess	20.6 ± 1.5	Upper Peoria Loess (unit 1)
UKK-1-215	UKK-1A-1A'	8.4 – 8.7	UIC 1694IR	Silt/Loess	27.3 ± 1.9	Lower Peoria Loess (unit 2)
UKK-1-415	UKK-1B-1B'	8.1 – 8.4	UIC 1699IR	Silt/Loess	23.5 ± 1.7	Lower Peoria Loess (unit 2)
UKK-2-344	UKK-2A-2A'	7.2 – 7.4	UIC 1696IR	Silt/Loess	27.3 ± 1.9	Lower Peoria Loess (unit 2)
UKK-2-544	UKK-2B-2B'	7.5 – 7.7	UIC 1702IR	Silt/Loess	28.8 ± 2.1	Lower Peoria Loess (unit 2)
UKK-1-215	UKK-1A-1A'	10.3 – 10.5	UIC 1701IR	Silt/Loess	34.6 ± 2.5	Roxana Silt (unit 3)
UKK-1-415A	UKK-1A-1A'	9.4 – 9.6	UIC 1700IR	Silt/Loess	47.2 ± 3.5	Roxana Silt (unit 3)
UKK-2-344A	UKK-2A-2A'	10.8 – 11.0	UIC 1697IR	Silt/Loess	39.6 ± 2.8	Roxana Silt (unit 3)
UKK-2-344A	UKK-2A-2A'	10.8 – 11.0	UIC 1697IRr (Duplicate)	Silt/Loess	41.1 ± 2.9	Roxana Silt (unit 3)
UKK-2-544	UK-2B-2B'	12.1 – 12.3	UIC 1732	Silt/Loess	70.1 ± 5.4	Unnamed Intermediate Loess (unit 4)
UKK-2-544	UK-2B-2B'	13.1 – 13.4	UIC 1733	Silt/Loess	58.1 ±4.5	Unnamed Intermediate Loess (unit 4)

[1] The IR designation indicates excitation by infrared diodes (880 ± 80 nm) by the multiple aliquot additive dose technique (Forman and Pierson, 2002).
[2] The GR designation indicates excitation by green light (514 ± 20 nm) by the multiple aliquot regenerative dose technique (Jain et al., 2003).
[3] The IRr designation indicates excitation by infrared diodes (880 ± 80 nm) by the multiple aliquot regenerative dose technique (Jain et al., 2003).
[4] All errors are at 1 sigma. OSL ages determined at Luminescence Dating Research Laboratory at Univ. of Illinois at Chicago.

Table 3. Summary Table of Zones of Possible Tilting and Warping - Proposed C-746-U Landfill, Paducah, Kentucky

Possible Large-Scale Structural Features	Cross Section Line	Constrained Between Cores	Structural Style[A]	Direction of Down Warping[B]	Amount of Vertical Separation in Feet (Maximum)	Youngest Unit Boundary Vertically Separated[C]		Estimated Age of Youngest Unit Vertically Separated Ka[D]
AA	UKK-1A-A’	UKK-1-180 to 250	W	S	5	Unit 5.1	Metropolis Formation	>125
BB	UKK-1B-B’	UKK-1-350 to 380	W	N	3	Unit 5.1	Metropolis Formation	>125
CC	UKK-1B-B’	UKK-1-405 to 430	W	N	2.25	Unit 4.0	Unnamed Intermediate Loess	53.6 to 75.5
DD	UKK-2A-A’	UKK-2-319 to 379	F (Antiform)	W and E	5	Unit 4.0	Unnamed Intermediate Loess	53.6 to 75.5

A: W = warping, F = folding
B: N= northside-down, S = southside-down; W = westside-down; E = eastside-down
C: Age of youngest stratigraphic basal boundary affected by possible warping
D: Ka = 1,000 years

Table 4. Summary of Features Having Distinct Elevation Changes in Stratigraphy - Proposed C-746-U Landfill, Paducah, Kentucky

Feature	Cross Section Line (UKK)	Feature Constrained Between Cores	Estimated Amount of Separation Max/Limit of Resolution[A] (ft)	Sense of Vertical Separation (Direction/ Style)[B]	Dip of Feature (H, M, L)[C]	Youngest Unit Boundary Vertically Separated[D]		Estimated Age of Youngest Unit Vertically Separated Ka[E]
A	1A – 1A'	UKK-1-200 to 220	2.0/0.4	S/N	L	Unit 4.0	(Unnamed Loess)	53.6 to 75.5
B	1A – 1A'	UKK-1-205 to 215A	2.0/0.3	N/R	M	Unit 5.1	(Metropolis Formation)	>125
C	1A – 1A'	QKK-1-215A to 220	1.75/0.5	N/N	H	Unit 5.2	(Metropolis Formation)	>125
D	1A – 1A'	UKK-1-220 to 225	1.25/0.3	S/N	H	Unit 5.1	(Metropolis Formation)	>125
E	1A – 1A'	UKK-1-230 to 235	1.75/0.5	S/N	H	Unit 5.2	(Metropolis Formation)	>125
F	1B – 1B'	UKK-1-350 to 380	3.0/0.4	S/R	M	Unit 4.0	(Unnamed Loess)	53.6 to 75.5
G	1B – 1B'	UKK-1-405 to 415	1.75/0.4	N/R	M	Unit 3.0	(Roxana Silt)	32.1 to 50.7
H	1C – 1C'	UKK-1-530 to 555	2.0/0.4	S/R	L	Unit 4.0	(Unnamed Loess)	53.6 to 75.5
I	1C – 1C'	UKK-1-565 to 575	3.25/1.0	S/N	H	Unit 4.0 (2.0/1.0)	(Unnamed Loess)	53.6 to 75.5
J	1C – 1C'	UKK-1-585 to 590	1.25/1.0	N/N	H	Unit 5.1 (2.0/1.0)	(Metropolis Formation)	>125
K	2A – 2A'	UKK-2-304 to 309	1.5/0.4	W/N	H	Unit 5.1	(Metropolis Formation)	>125
L	2A – 2A'	UKK-2-329 to 349	2.0/0.6	E+W/R	M	Unit 2.0	(Lower Peoria Loess)	21.8 to 30.2
M	2A – 2A'	UKK-2-349 to 354	2.0/0.3	W/N	H	Unit 5.1	(Metropolis Formation)	>125
N	2A – 2A'	UKK-2-354 to 359	1.5/0.3	E/N	H	Unit 5.1	(Metropolis Formation)	>125
O	2A – 2A'	UKK-2-354 to 364	1.0/1.9	W/R	M	Unit 4.0	(Unnamed Loess)	53.6 to 75.5

Feature	Cross Section Line (UKK)	Feature Constrained Between Cores	Estimated Amount of Separation Max/Limit of Resolution[A] (ft)	Sense of Vertical Separation (Direction/ Style)[B]	Dip of Feature (H, M, L)[C]	Youngest Unit Boundary Vertically Separated[D]		Estimated Age of Youngest Unit Vertically Separated Ka[E]
P	2A – 2A’	UKK-2-359 to 369	2.0/0.4	W/N	H	Unit 4.0	(Unnamed Loess)	53.6 to 75.5
Q	2B – 2B’	UKK-2-519 to 524	2.0/0.4	W/N	H	Unit 4.0	(Unnamed Loess)	53.6 to 75.5
R	2B – 2B’	UKK-2-549 to 554	1.0/0.5	E/N	H	Unit 5.2	(Metropolis Formation)	>125
S	2B – 2B’	UKK-2-579 to 589	1.5/0.4	W/N	H	Unit 4.0	(Unnamed Loess)	53.6 to 75.5
T	2B – 2B’	UKK-2-649 to 699	2.0/0.4	E/R	M	Unit 4.0	(Unnamed Loess)	53.6 to 75.5
U	2B – 2B’	UKK-2-669 to 679	2.0/0.4	E/N	L	Unit 3.0	(Roxana Silt)	32.1 to 50.7

A: Limit of resolution of unfaulted unit that lies directly above feature
B: Direction of inferred vertical separation (direction of down-thrown side)/apparent sense of vertical separation N = Normal; R = Reverse
C: H = High-angle (>60°); M = Moderate-angle (≤ 60° to 30° ≥); L = Low-angle (< 30°)
D: Age of youngest basal boundary with vertical separation
E: Ka = 1,000 years
(): Parenthesis indicate possible fault-like feature that comes “anomalously close” to the ground surface but is believed to be a result of DPT sampling complexities